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A TRIDENT SCHOLAR PROJECT REPORT

NO. 169

EXPLOSIVE CYCLOGENESIS: A CASE STUDY OF THE VETERANS' DAY STORM OF 11-12 NOVEMBER 1987.

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coupled with strong upper and lower level forcing, provides the mechanisms responsible for rapid intensification of these significant weather-producing storms. In this study, a case of explosive cyclogenesis is examined. It was discovered that the intensification phase of this storm, called the Veterans' Day Storm of November 1987, was related to the strong sea surface temperature (SST) gradient present off the east coast of the United States. The SST gradient was analyzed using Advanced Very High Resolution Radiometer (AVHRR) data. The upper and lower level forcing mechanisms were studied using conventional weather products from the National Meteorological Center and special analyses made available from the NASA Goddard Laboratory for Atmospheric Sciences in Greenbelt, MD. The presence of strong positive vorticity advection, significant upper level divergence, and an atmospheric lid were among the major contributors responsible for intensification of this storm.

U.S.N.A. - Trident Scholar project report; no. 169 (1990)

**EXPLOSIVE CYCLOGENESIS:
A CASE STUDY OF THE VETERANS' DAY
STORM OF 11-12 NOVEMBER 1987.**

A Trident Scholar Project Report

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ABSTRACT

An important breeding ground for explosive cyclone development is off the east coast of the United States, near Cape Hatteras. An important factor in cyclone development is the enormous energy requirement needed for explosive deepening of these systems. The presence of the warm Gulf Stream current in the western Atlantic provides a significant portion of this energy. This energy source, coupled with strong upper and lower level forcing, provide the mechanisms responsible for rapid intensification of these significant weather-producing storms.

In this study, a case of explosive cyclogenesis is examined. It was discovered that the intensification phase of this storm, called the Veterans' Day Storm of November 1987, was related to the strong sea surface temperature (SST) gradient present off the east coast of the United States. The SST gradient was analyzed using Advanced Very High Resolution Radiometer (AVHRR) data. The upper and lower level forcing mechanisms were studied using conventional weather products from the National Meteorological Center and special analyses made available from the NASA Goddard Laboratory for Atmospheric Sciences in Greenbelt, MD. The presence of strong positive vorticity advection, significant upper level divergence, and an atmospheric lid were among the major contributors responsible for intensification of this storm.

Acknowledgments

I would like to thank my Trident advisor Assoc Prof David R. Smith who gave me the inspiration to conduct and complete this research project. I would also like to express my deepest gratitude to George Huffman of the NASA Goddard Laboratory for Atmospheric Sciences for his assistance in preparing the numerous analyses that were used in this project. And finally I would like to thank my fiance Patricia McClure for her encouragement and tolerance during the final weeks of this project.

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I. Introduction

The prediction of severe weather phenomena has sparked the interest of meteorological researchers for many years. One forecasting problem that has eluded accurate prediction is explosive cyclogenesis. Cyclogenesis is the development and intensification of storms associated with the circulation about a low pressure center. These storms (cyclones) are important weather producers during winter months, especially in middle latitudes. Explosive cyclogenesis is defined as the rapid intensification of a cyclone marked by pressure falls of 24 millibars (mb) over a 24-hour period (Sanders and Gyacum, 1980). Recent studies suggest that explosive cyclogenesis is a maritime phenomenon that occurs most frequently along the western North Atlantic and Pacific oceans, and especially in regions of strong baroclinity (e.g., regions of strong horizontal temperature gradients as found in a frontal zone).

Two historical examples of explosive cyclogenesis are the gale that struck the HMS Queen Elizabeth II (QEII) on 10-11 September 1978 and the Presidents' Day Snow Storm of 18-19 February 1979. Neither storm was predicted by operational forecasters. These two extratropical cyclones were studied extensively by scientists seeking to identify measurable characteristics unique to explosive cyclogenesis and perhaps assist the forecaster in predicting similar storm systems.

A. Review of Past Studies

An important breeding ground for explosive storm development is off the east coast of the United States, near Cape Hatteras. The presence of the warm Gulf Stream current in the western Atlantic partially satisfies the enormous energy requirement for explosive deepening of extratropical cyclones. A critical factor involved in this process is the surface temperature gradient between the cold land mass along the east coast of the U.S. and the warmer Gulf Stream current. As cold air outbreaks move offshore, the atmospheric boundary layer interacts with the warm, moist ocean surface to initiate and intensify storms. The rate at which this process of intensification occurs is dependent upon the strength of the temperature gradient. Research has indicated that this temperature gradient and explosive cyclone development are in fact related (Carson, 1988). Rogers and Bosart (1986) compiled upper air data on 328 storms and discovered that rapidly developing cyclones had their beginnings in weak, shallow systems that later matured into intense cyclones characterized by strong baroclinity, strong upward motion, and low level conditional instability. The question that remains is what prevents this warm, moist, conditionally unstable air mass from being lifted and releasing its energy before generating into an intense cyclone? One possible explanation was developed by Green (1988) who acknowledged the possible contribution of an atmospheric lid.

Lid establishment occurs when a layer of dry air with a conditionally unstable lapse rate overlies cool, moist maritime air. The inversion, or lid, is located near 700 mb and has a sharp temperature increase with height compared to a temperature decrease typical of the standard atmosphere. Green's hypothesis was that if a strong lid condition existed upwind of the latent heat release areas, explosive development could occur. Suggested mechanisms that could be responsible for the weakening of the lid and subsequent explosive convection are upper-level positive vorticity advection (PVA) and a polar front jet (PFJ). Both conditions accommodate the intense upper level divergence necessary for these storms to develop.

In previous case studies of explosively developing cyclones, it became obvious that the primary problem in predicting these events was the relative scarcity of data. Conventional data are sparse over the oceanic regions except for occasional ship, aircraft, and buoy reports. Gyacum (1983a,b) used Seasat-A surface wind data along with ship, buoy and land reports to describe the synoptic scale thermodynamic and dynamic processes that are observed during explosive cyclogenesis. The data obtained proved inconclusive, because they could not accurately account for the explosive deepening that occurred. Uccelinni et al (1987) compiled data on the Presidents' Day Storm (18-19 February 1979) and discovered that atmospheric profiles of temperature

advection and other diabatic processes were too highly interrelated to be ranked as to their relative importance in explaining the event.

The use of remotely-sensed satellite data to study these storms at sea provides a possible solution to the inadequacy of conventional data. Research in the field of remote sensing techniques has yielded an invaluable data source to the operational forecaster. It was noted by Weldon (1977) that various cloud patterns occurred more frequently than others during explosive cyclogenesis. These cloud types included a thick deck of cirrostratus clouds with a well-defined, anticyclonically-curved northern and western edge. In addition, a comma-shaped cloud is almost always visible in the predevelopment stages (Carlson, 1980; Antagen, 1988). A third type of cloud signature is similar to the aforementioned one, except that it is wrapped around the circulation center. Jager (1984) observed similar cloud characteristics and reported that if these clouds were to overtake an existing frontal system, especially one with a developing wave pattern, rapid cyclogenesis could occur.

Williams (1985) confirmed the findings of Weldon (1977) after a study of satellite-observed cloud patterns in the western North Atlantic Ocean. He found that cloud development could be used to accurately predict explosive development 24-36 hours before it actually occurred. It is increasingly evident that use of remote sensing techniques can prove

invaluable in explosive cyclogenesis research. If coupled with the conventional data described above, remote sensing could assist with accurate and timely prediction of explosive cyclogenesis.

B. Purpose

The purpose of this project is to offer a systematic approach to explosive cyclogenesis prediction through the use of realtime data available to the meteorologist. The data that will be utilized in this project will be that gathered during the Veterans' Day Storm of 09-12 November, 1987.

The proposed approach to this project consists of three steps:

1. Evaluate extensive amounts of meteorological data products including a variety of horizontal fields and vertical atmospheric profiles (using conventional thermodynamic diagrams). Compare these profiles to those developed during past studies of cyclogenesis and note any distinguishing characteristics.

2. Process and evaluate satellite imagery (both in the visible and infrared spectrum) using the Digital Image and Processing System (DIPS) to determine any correlation between storm track and sea surface temperatures.

3. Incorporate all of the above data as a method of identification for developing explosive cyclogenesis and offer solutions to storm development and track prediction.

II. Synoptic Analysis

A. Precyclogenesis:

0000 UTC 10 NOVEMBER 1987

At 10/0000 UTC the National Meteorological Center (NMC) Surface Analysis (Fig. 1) places a high pressure system extending from central Canada to the northern panhandle of Texas with a central pressure of 1036 mb. On the Gulf coast, a low pressure system centered over eastern Louisiana dominates the region. This low pressure system has a central pressure of 1010 mb. Rain and thundershowers extend from the Gulf states northeastward along a quasi-stationary cold front to southern New England. Snow has begun to fall over central New York at this time. The 09/2325 UTC Radar Summary (Fig. 2) places cloud tops over the low pressure center at above 10,000 m. This is confirmed by the M_B enhanced 10/0001 UTC satellite image (not shown), a thermally enhanced picture used to delineate between the greater temperature ranges present in middle latitudes, with cloud-top temperatures well below -50° C in the region, indicative of extensive vertical development. An incipient low pressure center has begun to develop along the front over western Virginia and currently has a central pressure of 1019 mb.

At 850 mb (not shown), the low pressure system over eastern Virginia has yet to develop, but the more established low pressure system to the south is observed over central Louisiana. A strong temperature gradient extends from the

Great Lakes southeastward toward the South Carolina coastline with the low over central Louisiana well south of this baroclinic zone. A trough has begun to extend southward along the eastern United States toward the low pressure system.

The 500-mb analysis (not shown) places the low pressure system over eastern Texas with a trough extending northeastward into eastern Canada. Wind velocities are in excess of 35 m/s on the eastern portion of the trough accompanied by height falls ranging from 10 to 50 m. The height falls indicate the eastward movement and intensification of the upper level trough. Dewpoint depressions range from 15 to 20°C along the East Coast. The magnitude of this dewpoint depression indicates a cold, dry upper level air mass in the region.

The 250-mb analysis (Fig. 3) shows a jet maximum of 65 m/s located over central Ohio with a second maximum of 50 m/s over the western portion of the Gulf of Mexico. The location of the trough in the left front quadrant of the jet maximum over Ohio, a region of divergence, is favorable for intensification of the trough and future development of the cyclone (Chalfant, 1989). The location of the low over central Texas at 250 mb is an indication of the extent to which vertical development has occurred. Cyclone development in this region could be attributed to the presence of the second jet maximum to the south and the upper level divergence associated with it.

1200 UTC 10 NOVEMBER 1987

The surface analysis at 10/1200 UTC (Fig. 4) positions the low pressure system over northern Georgia with a central pressure of 1009 mb, a 1 mb drop since the 10/0000 analysis. An instability line marked by intense thundershowers with cloud tops in excess of 12,500 m extends from the low toward the Atlantic coast of central Florida to the southeast. Snow continues to fall in parts of central Pennsylvania and West Virginia while snow showers have begun in the northeast portion of New Hampshire and Vermont. Rain and drizzle are prevalent over much of the Atlantic seacoast. The high pressure system over the Midwest continues to develop and is currently measured at 1037 mb. Meanwhile, frontogenesis is occurring behind the original cold front that is now detached from the system. The original front extends southward into the Gulf of Mexico, while the once quasi-stationary front begins to move eastward of its original position at 10/0000 UTC.

The 850-mb analysis (not shown) centers the low over eastern Tennessee with the cyclone located on the warm side of an intense baroclinic zone along the North Atlantic coast. A high pressure ridge has developed to the west of the low and extends northeastward from the panhandle of Texas into the western Great Lakes region. Thermal advection, an important contributor to cyclone development, is moderate in the

vicinity of the low, and height falls of 10 to 30 m in the region of cold advection to the north indicate a deepening system at this time.

At 10/1200 UTC the 500-mb analysis (Fig. 5) shows a deepening of the trough to the west of the surface low with height falls of 10 to 90 m occurring along the southeastern boundary of the trough. The 500-mb analysis does not display a closed low center associated with the cyclone observed on the surface analysis, indicating that it is a shallow system at this time.

The 250-mb analysis at 10/1200 UTC (Fig. 6) indicates an increase in the jet stream velocity from 30 m/s at 10/0000 UTC to 60 m/s over northern Florida. The jet maximum over the mid-Atlantic seacoast remains unchanged, but the right rear quadrant of the jet, a region of upper level divergence, is currently positioned over the surface low. Height falls of up to 120 m are occurring to the northwest of the surface cyclone indicating a strengthening of the upper level trough.

0000 UTC 11 NOVEMBER 1987

At 11/0000 UTC, the surface analysis (Fig. 7) depicts two low pressure centers over coastal Virginia and central South Carolina, respectively. Central pressure for both systems is 1008 mb. The low centered over Virginia appears to have extensive vertical development to the east and southeast of its surface position as evidenced by the M_B

enhanced 11/0001 UTC satellite image (Fig. 8a). A comma cloud, indicative of PVA, is visible on the 11/0001 UTC satellite image to the west of the cyclone (Fig. 8b). Stations in the vicinity of the low over Virginia report declining pressures over the past six hours along the seacoast. Pressures remain steady or increase slightly in the vicinity of the low over South Carolina. A belt of snow showers extends from central Kentucky northeastward into parts of Maine and Nova Scotia while rain and drizzle continue over the central northeast portion of the East Coast. Mild to moderate thundershowers continue over the Carolinas.

The 850-mb analysis at 11/0000 UTC (Fig. 9) centers a single low along the Virginia coast, confirming the initial assessment from the 11/0000 UTC surface analysis that the low over South Carolina was shallow and not well developed. Strong thermal advection surrounds the cyclone that is still to the south of the baroclinic zone present in the 10/1200 UTC analysis. A high pressure ridge continues to develop to the west of the surface low and 500-mb trough, but height falls from 40 to 90 m to the northeast and 40 to 60 m to the northwest of the low indicate continued deepening of this surface cyclone.

The 500-mb analysis (Fig. 10) continues to show a deepening of the trough to the west of the surface low that has still yet to develop at the 500-mb level. Height falls of 140 m are reported over West Virginia thus indicating

continued deepening of the upper level trough to the west of the surface low. The trough continues to propagate eastward from its 10/1200 UTC position.

The jet maximum at 250 mb (not shown) has intensified from 55 m/s over northern Florida at 10/1200 UTC to 70 m/s at 11/0000 UTC. Height falls in excess of 210 m over West Virginia confirm the intensification of the trough to the west of the surface low. Strengthening of the jet maximum, currently 45 m/s over Cape Hatteras, North Carolina, and development of the surface low is anticipated as the trough moves eastward and over the surface cyclone.

B. Cyclogenesis:

1200 UTC 11 NOVEMBER 1987

The 11/1200 UTC surface analysis (Fig. 11) places the low pressure center approximately 160 nm due east of the DelMarVa peninsula at 38°N, 71°W with a central pressure of 1003 mb. The low has intensified at a rate of 1.3 mb/hr in the previous three hours. Snow has begun to fall from the Carolinas northeastward into western New York with 24 hr accumulations of up to 12 cm in Pennsylvania and New York. The high pressure ridge to the northwest of the low now extends from central Texas northeastward to New Foundland with a central pressure of 1032 mb. The M_8 enhanced 11/1201 satellite image (Fig. 12) shows extensive low to middle level cloud cover over the eastern U.S. while extensive vertical

convection at 40°N, 65°W is occurring. This convection may indicate that the low is actually centered northeast of its position on the surface analysis. The low level clouds offshore appear to be aligned parallel to the strong sea surface temperature gradient along the Gulf Stream's North Wall indicating a substantial influence on the marine boundary layer (MABL) in the region.

The 850-mb analysis (Fig. 13) shows strong thermal advection taking place to the southwest and northeast of the cyclone respectively. Moist advection is occurring to the east of the low. Height falls of 20 to 50 m continue to the east and northeast of the low center now positioned over south central Virginia. The strong temperature gradient runs parallel to the East Coast with its main axis passing through the cyclone.

At 500 mb, the 11/1200 UTC analysis (Fig. 14) centers the cyclone over southern Ohio. Height falls of 110 m over West Virginia and 140 m over northern Georgia indicate an intensification of the 500-mb trough that has begun to pass over and envelop the low pressure center.

The jet maximum at 250 mb (not shown) remains largely unaffected with maxima of 50 m/s over the Carolinas. The low is placed over central Ohio in agreement with the 500-mb analysis. The extent of vertical development in indicated by the placement of the low at this level. Further

intensification and upper level forcing is expected due to height falls in excess of 150 m to the southwest of the cyclone.

0000 UTC 12 NOVEMBER 1987

The 12/0000 UTC Surface Analysis (Fig. 15) shows the now occluded cyclone off the Delaware sea coast at 38°N, 73°W with a central pressure of 990 mb, a 13 mb decline over the past 12 hrs. In agreement with the position of the low center on the surface analysis, the 12/0001 UTC satellite image (Fig. 16) shows cyclonic circulation in the low level cloud structure. Cloud top temperatures to the northeast of the cyclone indicate extensive vertical development in the warm sector of the cyclone with cumulonimbus clouds extending behind and southward forming a well defined line along the cold front. The high level clouds over Virginia that extend northward into New Hampshire are associated with the intense snowfall that is occurring in the region.

The 850-mb analysis (not shown) shows continued development and intensification of the surface low. Height falls of 80 m are occurring around the low that is now centered at approximately 39°N, and 74°W. Strong warm and cold advection around the cyclone continues at this time.

The 500 and 250-mb analyses (not shown) reflect the rapid intensification of the cyclone at this time. Height falls in excess of 200 m at the 500-mb level continue along the trough

axis that is now positioned over the cyclone. The jet maximum, currently 65 m/s, is positioned to the southeast of the cyclone providing the intense upper level divergence necessary for development at the observed rate of 13 mb over the past 12 hrs.

1200 UTC 12 NOVEMBER 1987

At 12/1200 UTC (Fig. 17) the cyclone is positioned at 41°N, 67°W with a central pressure of 972 mb, a 31 mb pressure fall over the past 24 hrs. The deepening rate classifies this cyclone as explosive. From 12/0000 to 12/0300 UTC the cyclone deepened at a rate of 3 mb/hr, the most rapid deepening rate observed during the life cycle. Snow accumulations of up to 36 cm were recorded at Dulles International Airport and the surrounding metropolitan Washington D.C. area. The pressure remained at 972 mb until the cyclone began to dissipate in the cold waters of the North Atlantic. The dynamics of this cyclone are discussed in the following chapter.

III. Discussion

A. Dynamic effects

The upper and lower forcing mechanisms involved in explosive development of the Veterans' Day Storm are best understood by examining the relationship of omega (w: vertical velocity expressed in pressure coordinates, where w < 0 indicates rising motion) to cyclone development. There are several methods to determine or infer the vertical motion in the atmosphere. Two common expressions which permit an analysis of vertical velocity and cyclone development are the vorticity equation and the omega equation. The vorticity equation (Eq. 1) expresses the time rate of change of absolute vorticity ($\zeta + f$) in terms of vorticity concentration due to mass convergence (see Appendix 1. for definition of terms).

Vorticity Equation.

$$\frac{d}{dt}\left(\zeta + f\right) = -\left(\zeta + f\right) \nabla \cdot V_H$$

[Eq.1]

Perhaps a better expression is the omega equation (Eq. 2).

Omega Equation.

$$\underset{A}{\left[\nabla^2 + \frac{f_0 \partial^2}{\sigma \partial p^2}\right]} w = \underset{B}{\frac{f_0 \partial}{\sigma \partial p}\left[V_g \cdot \nabla\left[\frac{\nabla^2 \Phi}{f_0} + f\right]\right]} + \underset{C}{\frac{1}{\sigma} \nabla^2\left[V_g \cdot \nabla\left[-\frac{\partial \Phi}{\partial p}\right]\right]}$$

[Eq. 2]

The omega equation when compared to the vorticity equation is superior because the omega equation does not require knowledge of vorticity tendency and horizontal wind velocity as does the vorticity equation. A treatment of the omega equation utilizing quasi-geostrophic theory follows (Holton, 1979).

There are several advantages in using the omega equation. Vorticity in the omega equation can be approximated using only observations of geopotential height (Φ) which are routinely measured. Further, the omega equation is a diagnostic equation that can be utilized even though horizontal wind fields or vorticity tendencies are not known (Holton, 1979). For these reasons, the omega equation can provide a reasonable analysis of the dynamics that occurred in the atmosphere during the Veterans' Day Storm.

In Eq. 2 there are three important terms involving vertical velocity (term **A**), differential vorticity advection (term **B**), and thickness advection (term **C**). Diabatic and frictional effects have been neglected since their effect is significantly smaller than terms **A**, **B** and **C**.

Term **A** represents the Laplacian of w. Since term **A** involves the second derivative in space of the w-field, which generally has wave-like disturbances in the atmosphere, it can be easily shown that term **A** is directly proportional to the magnitude of vertical velocity. Positive values of term **A** correspond to rising vertical motion while negative values indicate sinking motion.

Differential vorticity advection (term B) is related to the rate of increase with height of advection of absolute vorticity, expressed in terms of the Laplacian of geopotential height ($\nabla^2\Phi$). Falling geopotential height (Φ) is reflected by an intensification of the 1000-500 mb thickness gradient, which implies development of a surface low. Therefore, a decreasing value of Φ suggests increasing positive vorticity and upward vertical motion. Vorticity advection at the surface is small due to nearly circular flow, while at the 500 mb level positive vorticity advection (PVA) is at a maximum over a surface cyclone. Therefore term B, the vertical change of vorticity advection, is positive in the vicinity of the surface cyclone. As a result, the surface cyclone presents a reduction in 1000-500 mb thickness, an increase in PVA, and an increase in upward vertical motion ($w < 0$), all indicative of cyclone development (Holton, 1979; Chalfant, 1989).

Thickness advection (term C) is directly related to thermal advection, since warm air produces expansion in an air column. Thermal advection is relatively small over the cyclone center where PVA is at a maximum. In regions of warm air advection, normally to the south and east of a cyclone, positive thickness advection is occurring to maintain hydrostatic balance in the atmosphere. Warm advection enhances upward vertical motion, so term C is positive. In the absence of differential vorticity advection, w is negative indicating rising motion. The opposite argument holds true

for cold air advection, which occurs west of the surface cyclone. To go one step further, it should be recognized that warm advection implies increasing 1000-500 mb thickness. This occurs to the east of the surface cyclone below the upper-level ridge. As the ridge aloft intensifies, negative vorticity or anticyclonic flow aloft also increases. If geostrophic balance is to be maintained, horizontal divergence is necessary to account for the negative vorticity. This divergence then, in accordance with continuity of mass, requires that upward vertical motion occur to the east of the cyclone to replace the diverging air at the upper levels. Similar arguments hold for subsidence in regions of cold advection beneath the 500 mb trough to the west of the surface cyclone (Holton, 1979).

Another important term in the Omega equation is the static stability parameter (σ). Static stability expresses the difference in potential temperatures (θ) between the 1000 and 500-mb levels. Because σ is in the denominator, small values of σ indicate conditions conducive for upward vertical motion. If a parcel of air is lifted dry adiabatically and is warmer than the surrounding atmosphere, the value of σ will be small. Small σ values increase forcing by terms A, B, and C, which results in upward vertical motion and continued cyclone development. A decrease in static stability can result from surface warming or an influx of a cold upper-level airmass above the surface layer, thereby destabilizing the

vertical air column. While examining the affects of PVA, thermal advection, upper-level divergence and their contribution to the development of the Veterans' Day Storm, two periods during the intensification phase will be examined. The periods of interest are 0000 UTC 11 November and 1200 UTC 11 November 1987.

B. Storm Development

At 11/0000 UTC, the 500-mb height and absolute vorticity analyses (Fig. 18) show the trough axis extending southeastward from the Great Lakes into Louisiana. The vorticity maximum is $+18 \times 10^{-5}s^{-1}$ over the Great Lakes and north of Ohio. The 500-mb trough is located over a region of strong lower level cold advection as indicated by the 11/0000 UTC 850 mb analysis (Fig. 9). This region of cold advection has resulted in height falls of up to 140 m to the east of the 500-mb trough over West Virginia . The height falls east of the trough axis indicate an intensification of the horizontal pressure gradient resulting in cross-isobaric flow at the surface. This flow results in strengthened low level convergence. Figure 19 exhibits strong convergence at low levels up to 500 mb in the vicinity of the surface low, with a maximum value of $-25 \times 10^{-9}s^{-1}$ (negative values indicate convergence). Divergence occurs aloft above 250 mb which enhances storm development. In addition, a 500-mb horizontal vorticity advection field of $+1.5 \times 10^{-9}s^{-1}$ exists in the

region of the surface low (Fig. 20). This is an indicator of eastward propagation of the 500-mb trough. Vertical profiles of thermodynamic properties over the area of interest are quite revealing. Figure 21 is a vertical cross section of the atmosphere from Peoria, IL (PIA) eastward to Dayton, OH (DAY), Huntington, WV (HTS), Greensboro, NC (GSO) and Cape Hatteras, NC (HAT). The isolines denote constant values of equivalent potential temperature through this area. The packing of isolines in the lower atmosphere (near 850 mb) indicates the presence of a polar front that extends southward across the eastern U.S. as described in chapter 2 (Fig. 7).

Vertical profiles of temperature and dewpoint for two stations in the area of interest are analyzed in Figures 22 and 23. In Figure 22, the profile of temperature and dewpoint over Cape Hatteras, NC (HAT) at 11/0000 UTC indicates a relatively dry air mass above 550 mb while below 900 mb it is moist and warm (surface temperature of 20°C). No temperature inversion exists at this time. By comparison, Dulles International Airport (IAD) at 11/0000 UTC (Fig. 23), has a strong temperature inversion from 970 to 800 mb that exists above a relatively moist boundary layer. This inversion denotes the position of the polar front over IAD at this time, while a cold, dry airmass exists below this layer with a surface temperature of 0°C.

The 11/0000 UTC 290 K isentropic flow (Fig. 24) indicates that a possible source of low level moisture (below 850 mb) is the relatively warm, moist air flowing westward from over the warm Gulf Stream current off the east coast of the United States. Infusion of low level moisture contributes to destabilization of the air in the vicinity of the developing storm and enhances vertical motion. In addition, surface warming in the region of the cyclone, as well as the upper level cooling above 800 mb as depicted by advection of cold air along the 300 K surface (Fig. 25), is responsible for a decrease in static stability and the intense vertical development that occurs by 11/1200 UTC.

The 11/1200 UTC 500-mb height and absolute vorticity analyses (Fig. 26) confirm the intensification of the storm as the 500-mb height contours (solid lines) dig southward. The absolute vorticity maximum of +18 x $10^{-5}s^{-1}$ (dashed lines) is centered over the 500-mb low, which at this time extends from Georgia to northern West Virginia. The 500-mb trough is expected to intensify due to the strong cold advection at the 850-mb level and height falls of 140 m over northern Georgia (Fig. 13). Moderate warm advection is occurring to the northeast of the cyclone and has resulted in intense vertical convection at 40°N, 65°W (Fig. 12). Horizontal advection of 500-mb absolute vorticity (Fig. 27) has nearly doubled over the surface low with a maximum value of 2.5 x $10^{-9}s^{-1}$ over central Virginia. Divergence above 450 mb (Fig. 28) has

intensified since the 11/0000 UTC analysis to a maximum of $+13 \times 10^{-6}s^{-1}$ at 11/1200 UTC. The intensification of upper level divergence, necessary for continued deepening of the cyclone, can be attributed to intensification of the jet stream winds as indicated in the vertical wind profile (see wind barbs) for HAT at 11/1200 UTC (Fig. 29). Wind speeds in the jet intensified from 35 m/s at 11/0000 UTC to 60 m/s at 11/1200 UTC, acting as an exhaust mechanism to allow further deepening of the cyclone. The 11/1200 UTC 290 K isentropic flow analysis (Fig. 30) clearly shows a well defined cyclonic circulation around the low center over Virginia near the 800-mb level. This analysis also suggests entrainment of warm, moist air flowing westward from the warm ocean current offshore. The northeasterly winds at the surface provide additional humidity for the warm, moist air mass (note saturated layer below 720 mb) at HAT (Fig. 31). This in turn influences vertical mixing in the lower troposphere.

The temperature-dewpoint profile at IAD (Fig. 32) displays features which prevent free convection in the boundary layer. Above 500 mb, a continental airmass has affected the vertical profile over Dulles at 11/1200 UTC intensifying the drying aloft. An inversion extends from 900 mb to 700 mb which suppresses free convection. The 300 K analysis (Fig. 33) continues to show southwesterly flow of a dry continental airmass above 700 mb. Green (1988) found that cold dry air above a warm moist boundary layer coupled with

a low level inversion may create an atmospheric lid. In the present case, such an atmospheric lid exists (at 560 mb) as shown in Fig. 32. This lid prevented the vertical mixing of the warm moist boundary layer with the cold upper level air mass. This resulted in continued sensible heat and moisture addition at the lower levels. As a result, when the airmass moved downstream of this lid, the intensity of vertical convection was enhanced which led to explosive deepening of the cyclone.

The aforementioned analyses suggest destabilization of the lower troposphere below 700 mb. This coupled with upper level forcing resulted in the intense vertical development of this explosive cyclone. By 12/0000 UTC the storm was deepening at a rate of 3 mb/hr until it moved into the cooler slope water to the north of the Gulf Stream.

C. Influence of Sea Surface Temperature on Storm Track.

It was hypothesized at the onset of this investigation that the strong sea surface temperature (SST) gradient along the North Wall of the Gulf Stream may have influenced the track this storm followed through its life cycle. The first step to test this hypothesis was to obtain an SST profile of the western Atlantic that reflected conditions prior to development of the storm. An image from 9 November 1987 (Fig.

34) was selected because this date provided the best cloud-free picture of the region during the period preceding the storm.

The data set used was from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA 9 satellite. From this digitized data set, algorithms were performed, using the Naval Academy's Digital Imaging Processor System (DIPS) to remove any atmospheric constituents that may inhibit accurate measurement of surface temperature (i.e., water vapor, atmospheric pollutants, volcanic ash, etc). This data was then converted to an SST profile that was calibrated to within 1-1.5°C of actual values obtained from drifting buoy data.

The sea surface temperature profile in Fig. 34 can be used to observe and analyze oceanic and atmospheric phenomena. When examining the SST profile, the warmer Gulf Stream waters (approximately 23-29°C) are lighter than the cooler slope and shelf waters (approximately 10-18°C) to the north (Fig. 34). Cold eddies, small cyclonic features on the ocean surface, appear to the south of the strong North Wall SST gradient. Due to their cooler temperatures (approximately 21 °C), cold eddies stand out prominently among the warmer waters of the Gulf Stream.

A problem with this method of remote analysis of the SST field is cloud cover (denoted by the unusually cold temperatures observed to the north and south of the slope

water), especially during the winter months along the east coast. A technique often used to solve the problems encountered when cloud cover is prevalent over the observation area is to take several satellite observations over a short time period (usually 7 days). This allows for the possibility that portions of the observation area might be cloud free at one point during the time period. The satellite images are then calibrated as before then stacked over the observation area. Since cloud top temperatures are much colder (values that are often below 5°C) than sea surface temperatures, maximum values can be obtained through the stack of images yielding accurate sea surface temperatures for the region. The scarcity of clouds on 9 November 1987 allowed for the best period to observe the usually seasonal position of the Gulf Stream current and North Wall and analyze its influence on the Veterans' Day Storm.

Marine atmospheric boundary layer (MABL) circulations forced by Gulf Stream SST gradients were extensively examined by Warner et al. (1990). They discovered that the strength and resolution of the SST gradient had a significant impact on models simulating lower level forcing in the MABL below 800 mb. More specifically, the strong SST gradient produced horizontal temperature gradients below 950 mb 2-3 times larger than normal, increased horizontal velocities (stagnant air produced velocities of up to 7 m/s within 12 hrs), and significantly different spatial characteristics of vertical

velocities across the gradient. Heat and moisture fluxes were also enhanced in the region, though they were largely dependent on the wind velocity. The aforementioned results all contributed to MABL circulation that through differential thermal forcing may have an impact on cyclogenesis. The investigation of the Veterans' Day Storm also suggests a contribution of the MABL during storm development based on storm track, intensification, and satellite imagery analysis.

It was discovered that the SST gradient observed off the eastern U.S. coast had a definite impact on storm track during the development stage of this explosive cyclone (Fig. 35). After the storm reached its lowest pressure of 972 mb at 12/0900 UTC just north of the North Wall, the storm began to track in response to the 500-mb flow pattern despite its failure to do so during the development phase of the cyclone (see Table 1, Fig. 14 and 35). In addition, it is suggested that the proximity of the cyclone to the strong SST gradients, which often had values of up to 3°C/km along the North Wall, may have influenced the deepening rate of this cyclone. As reflected by the reduction in deepening rate in Figure 36, the cyclone's rate of development began to diminish following its departure from the 20°C contour along the North Wall and into the cooler slope water to the north. Though other factors may have influenced the deepening rate reduction, these could not be addressed due to data scarcity over this region. Satellite signatures in the region of the North Wall

provide some indication of the influence the sea surface temperature gradient may have had despite the scarcity of conventional data.

STORM CENTER DATA
11-12 NOVEMBER 1987

TIME (UTC)	LAT/LON (N/W)	SST (C)	PRESSURE (mb)	MB/HR
00	37.5/74	20	1008	
03	37.5/73.5	22	1008	0.0
06	37.5/73.5	22	1007	0.3
09	37.5/73.5	22	1007	0.0
12	37.5/71	26	1003	1.3
15	36.5/74	21	1000	1.0
18	37/73	21	997	1.0
21	37/72.5	24	994	1.0
00	38/73	23	990	1.3
03	39/70	22	981	3.0
06	39.5/69	19	976	1.7
09	40.5/69	12	972	1.3
12	41.5/67	13	972	0.0
18	44/63	11	972	0.0
00	46/60	10	970	0.7

Table 1. Storm center data.

The M_8 enhanced satellite image at 1201 UTC on 11 November 1987 (Fig. 12) describes the sea surface temperature gradient's influence on the MABL. As was described in chapter 2, low level convective clouds were found to be oriented parallel to and above the North Wall off the coast of Cape Hatteras, NC. These low level clouds were influenced by upward vertical motions in the region caused by the surface heating over the strong temperature gradient located in the region (Fig. 34). This finding supports Warner, et al. (1990) and suggests a possible relationship between MABL circulations and the onset of explosive cyclogenesis.

IV. Conclusions

This study suggests a mechanism occurring in the lower troposphere that resulted in enhanced vertical forcing in the region surrounding the cyclone. Destabilization of the lower troposphere across a strong baroclinic zone coupled with upper level forcing mechanisms such as intensification and eastward propagation of the 500-mb trough over the surface low, differential vorticity advection, thermal advection, as well as divergence associated with the polar jet stream all contributed to the explosive nature of this storm.

Though the cyclone intensified 35 mb in 24 hrs, its deepening rate of up to 3 mb/hr by 12/0000 UTC, just prior to leaving the warm waters of the Gulf Stream, suggests that the strong temperature gradient across the North Wall may have influenced the rate of development and track of the Veterans' Day Storm. The storm developed and tracked along the North Wall where the temperature gradient is strongest. However, when the storm reached its maximum intensity at 0900 UTC 12 November 1987, it tracked in response to the upper level steering current. The track at this point then became typical of most extratropical cyclones.

Though conventional data in the region of the cyclone became scarce to nonexistent once the developing cyclone moved offshore, satellite imagery provided substantial clues as to the dynamics that were occurring near the cyclone. The current

study proposes no definitive solution to storm track and prediction, however some indications are offered. The comma cloud that developed 15 hrs prior to the storm's development (Fig. 8b) as well as the low level clouds that developed in response to MABL thermal forcing (Fig. 12) were influenced by the strong SST gradient present in the development area. These suggest predictors for the track of the cyclone and the mechanisms responsible for explosive development of these storm systems.

Though this study examines only one case of explosive cyclogenesis, it has been demonstrated that the use of satellite imagery for both meteorological and oceanic applications may greatly enhance our understanding of the air-sea interactions occurring during explosive development of cyclones. Obviously additional research is required to improve our capability to predict their occurrence. Two recent field projects called the Genesis of Atlantic Lows Experiment (GALE) and the Experiment on Rapidly Developing Cyclones over the Atlantic (ERICA) provide extended data sets not normally available to the operational forecaster or the researcher. Examination of the data sets from these two major field projects will provide additional information that should answer some of the questions that remain in regards to this still misunderstood phenomenon.

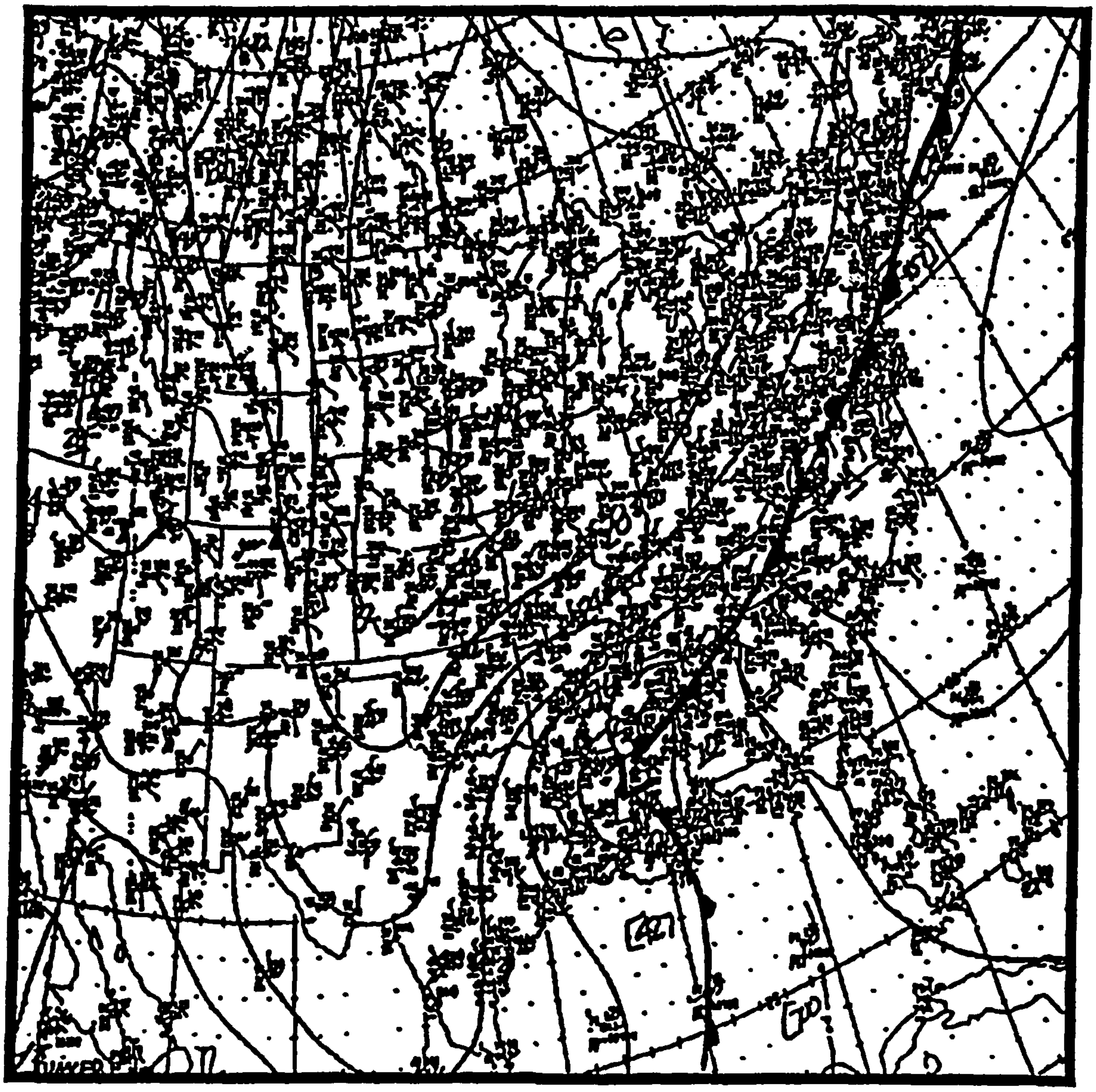

Figure 1. NMC Surface analysis for 0000 UTC, 10 November 1987.

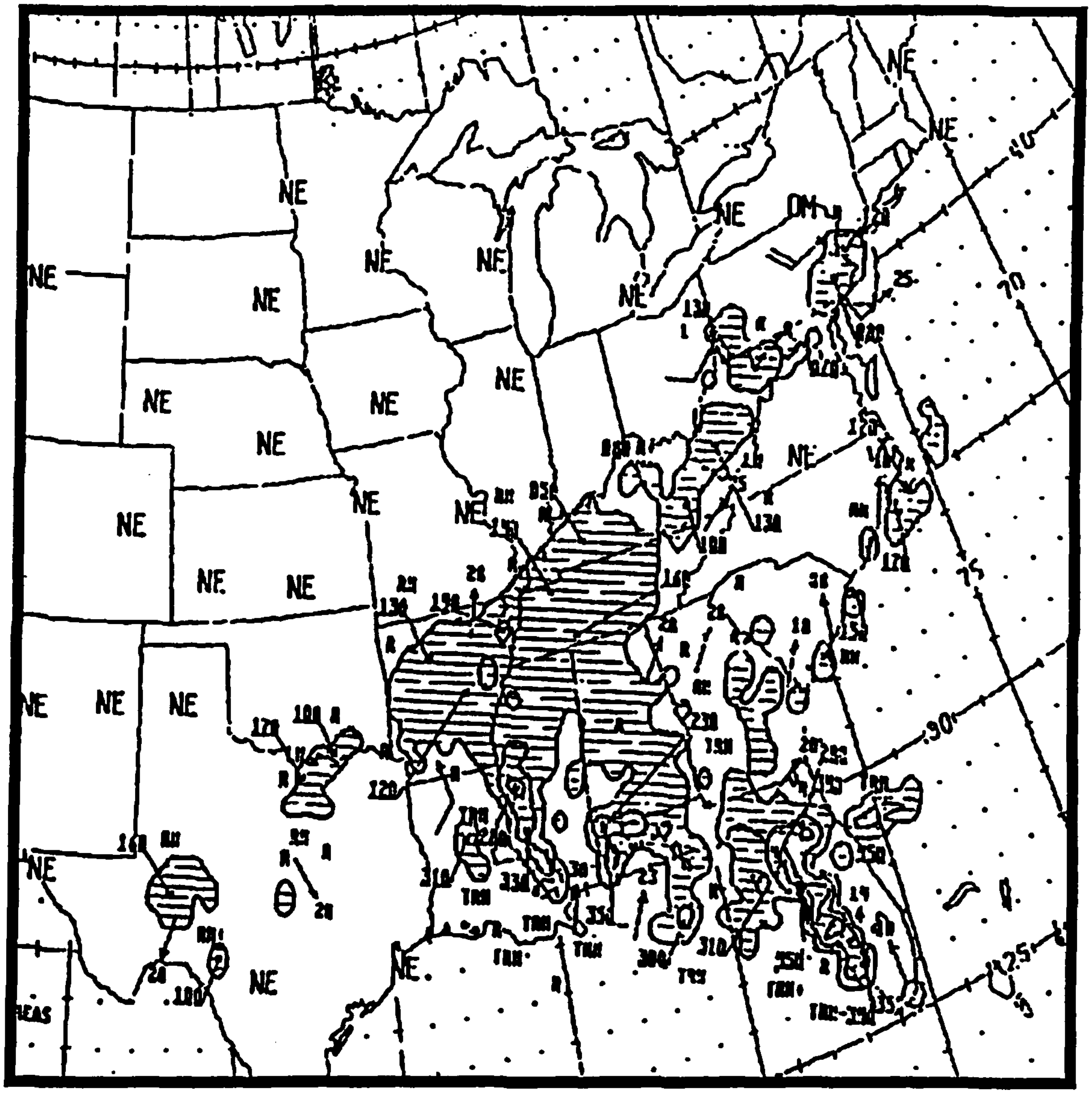

Figure 2. Radar summary for 2325 UTC, 09 November 1987. Shaded regions indicate clouded areas with bases and tops in hundreds of feet. Arrows indicate velocity in knots of the cloud cell.

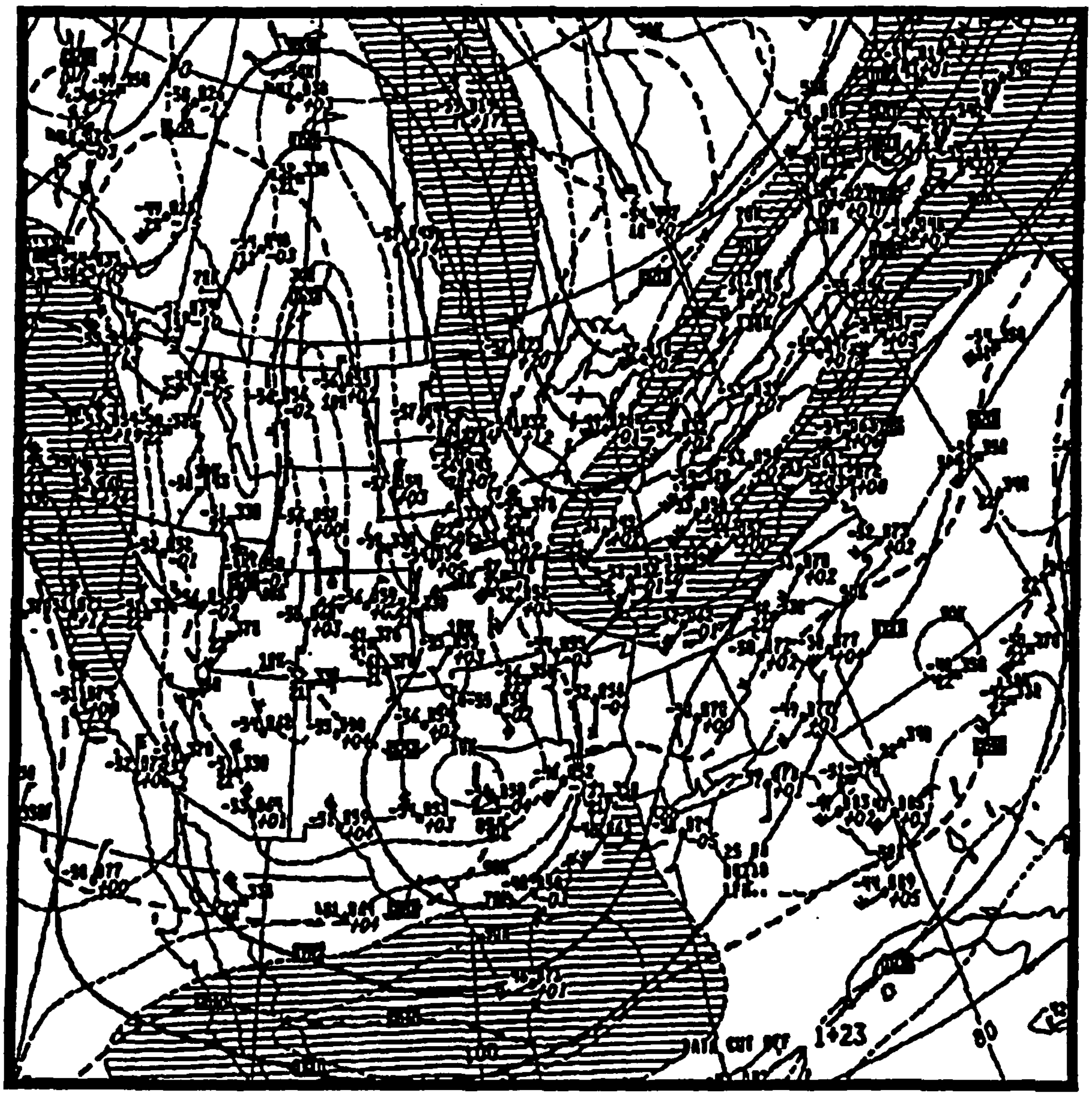

Figure 3. NMC 250 mb heights (solid lines in meters) and isotachs (wind barbs in knots) for 0000 UTC, 10 November 1987.

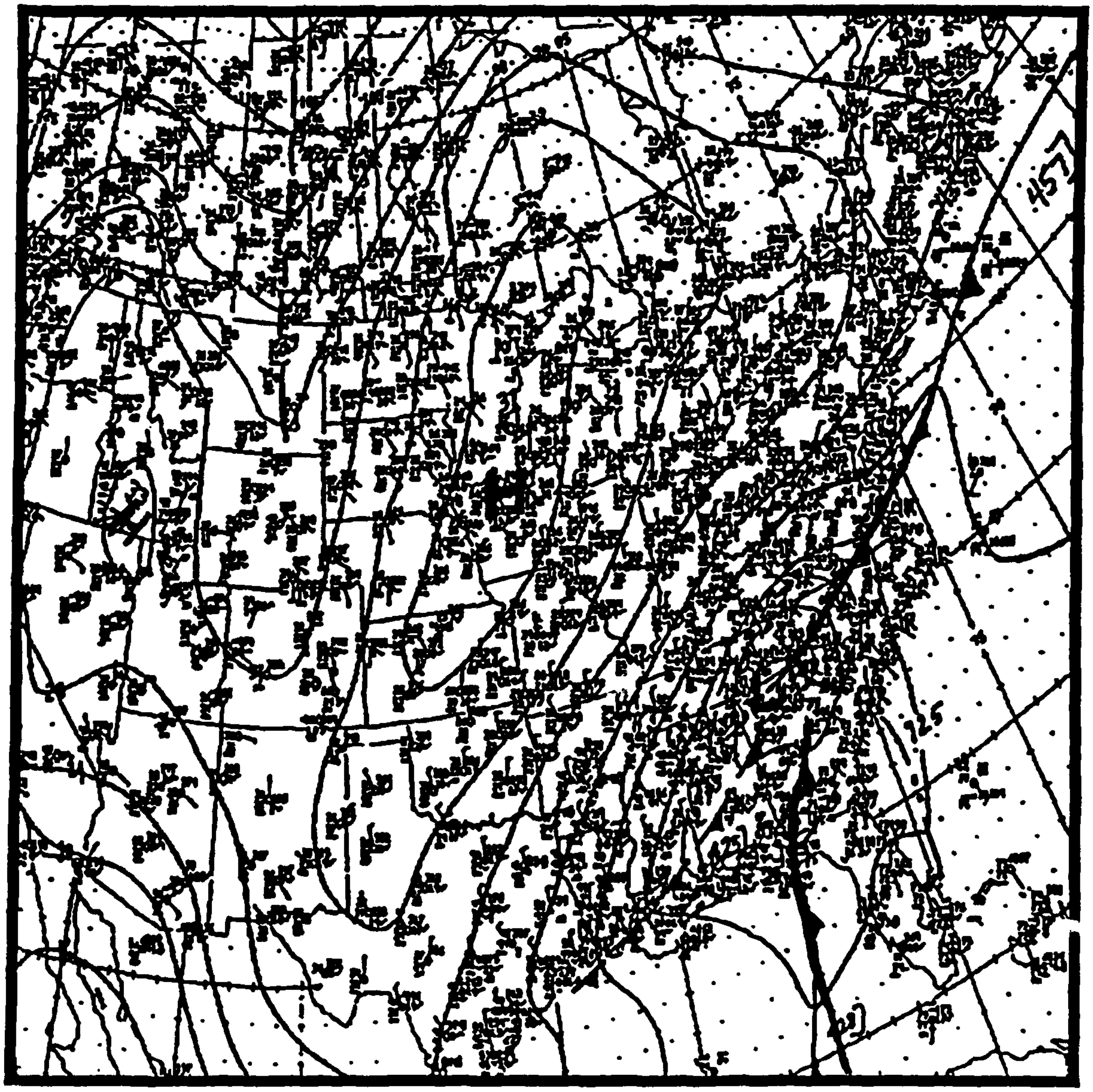

Figure 4. Same as Fig. 1 except at 1200 UTC, 10 November 1987.

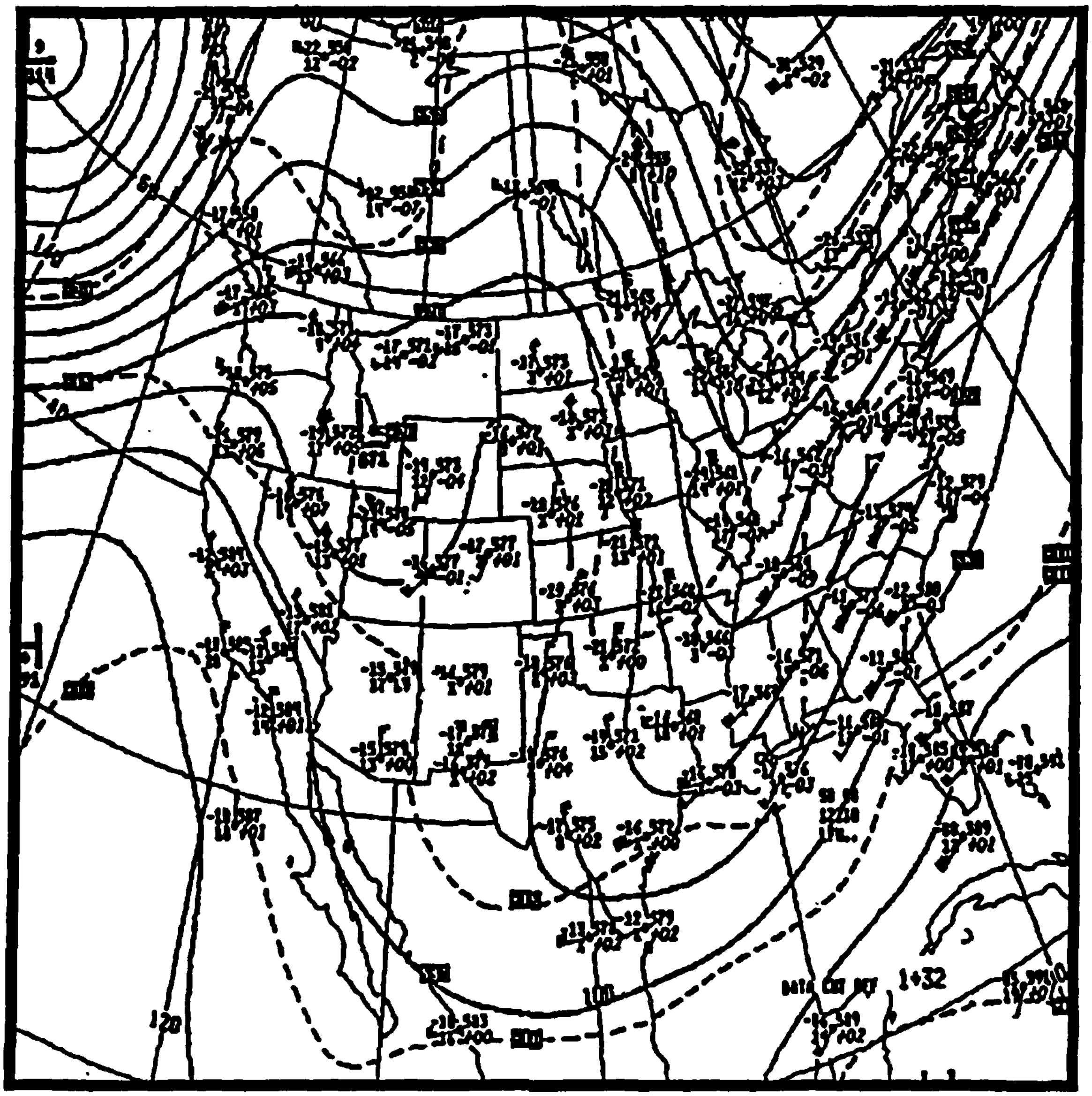

Figure 5. NMC 500 mb analysis for 1200 UTC, 10 November 1987

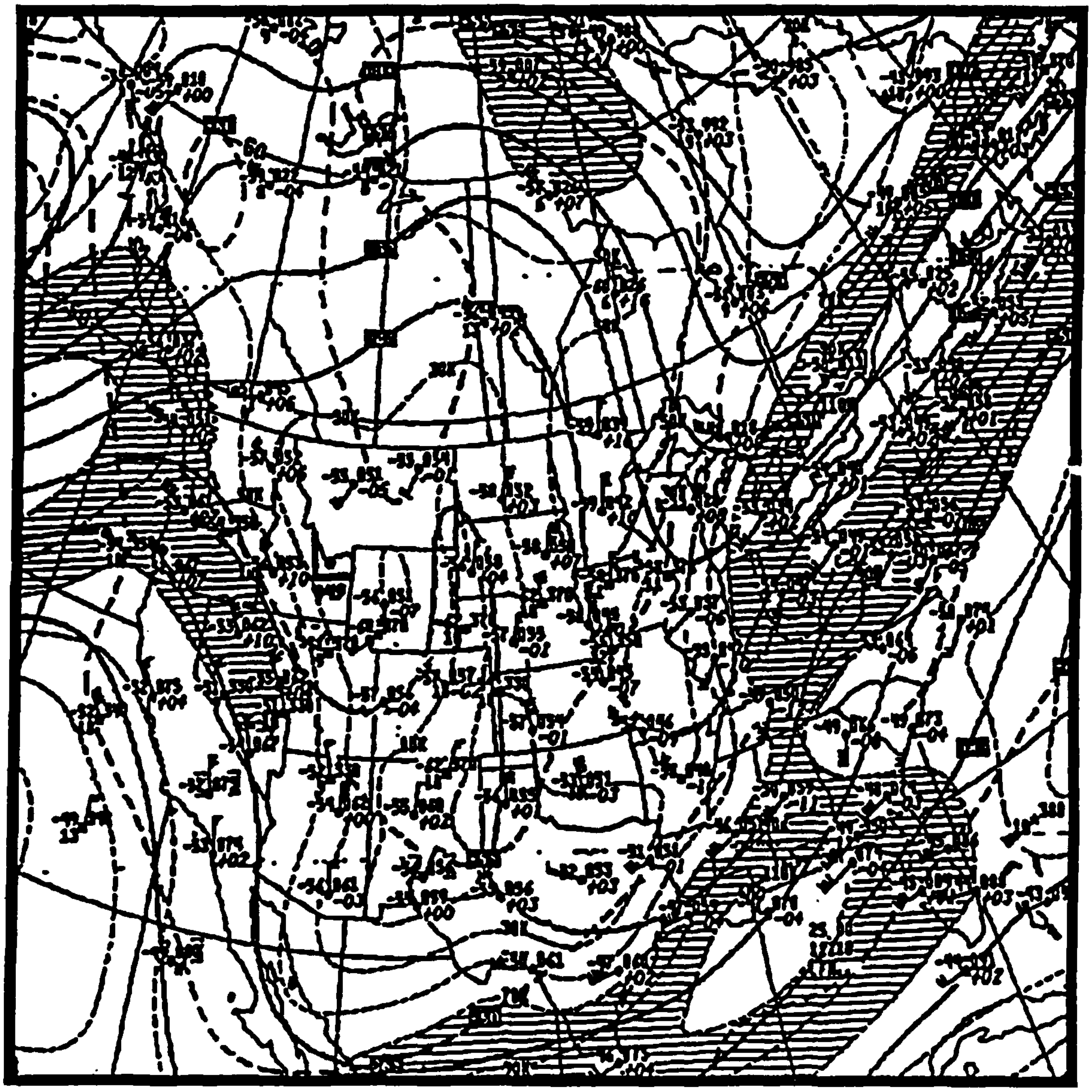

Figure 6. Same as Fig. 3 except at 1200 UTC, 10 November 1987.

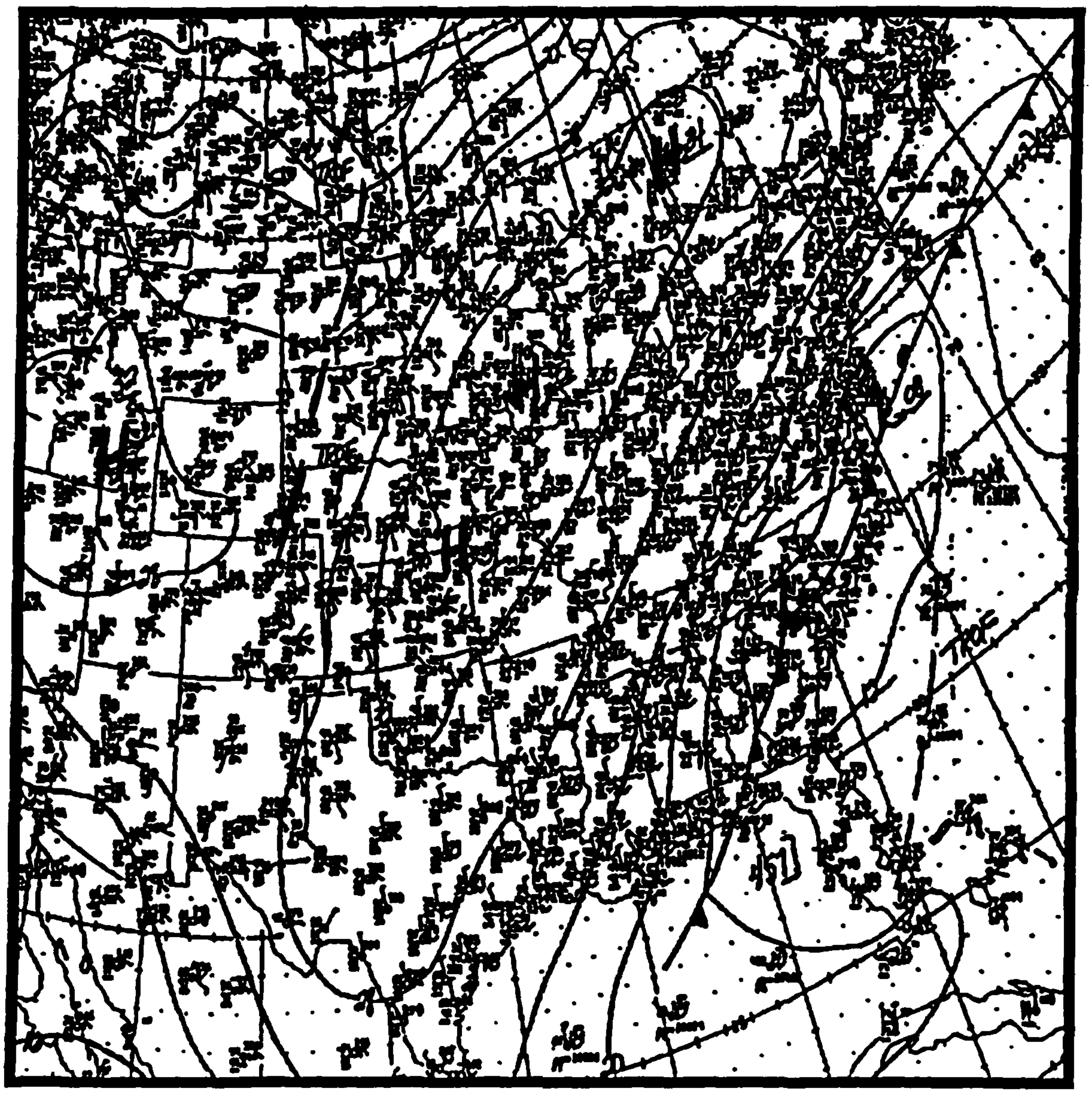

Figure 7. Same as Fig. 1 except at 0000 UTC, 11 November 1987.

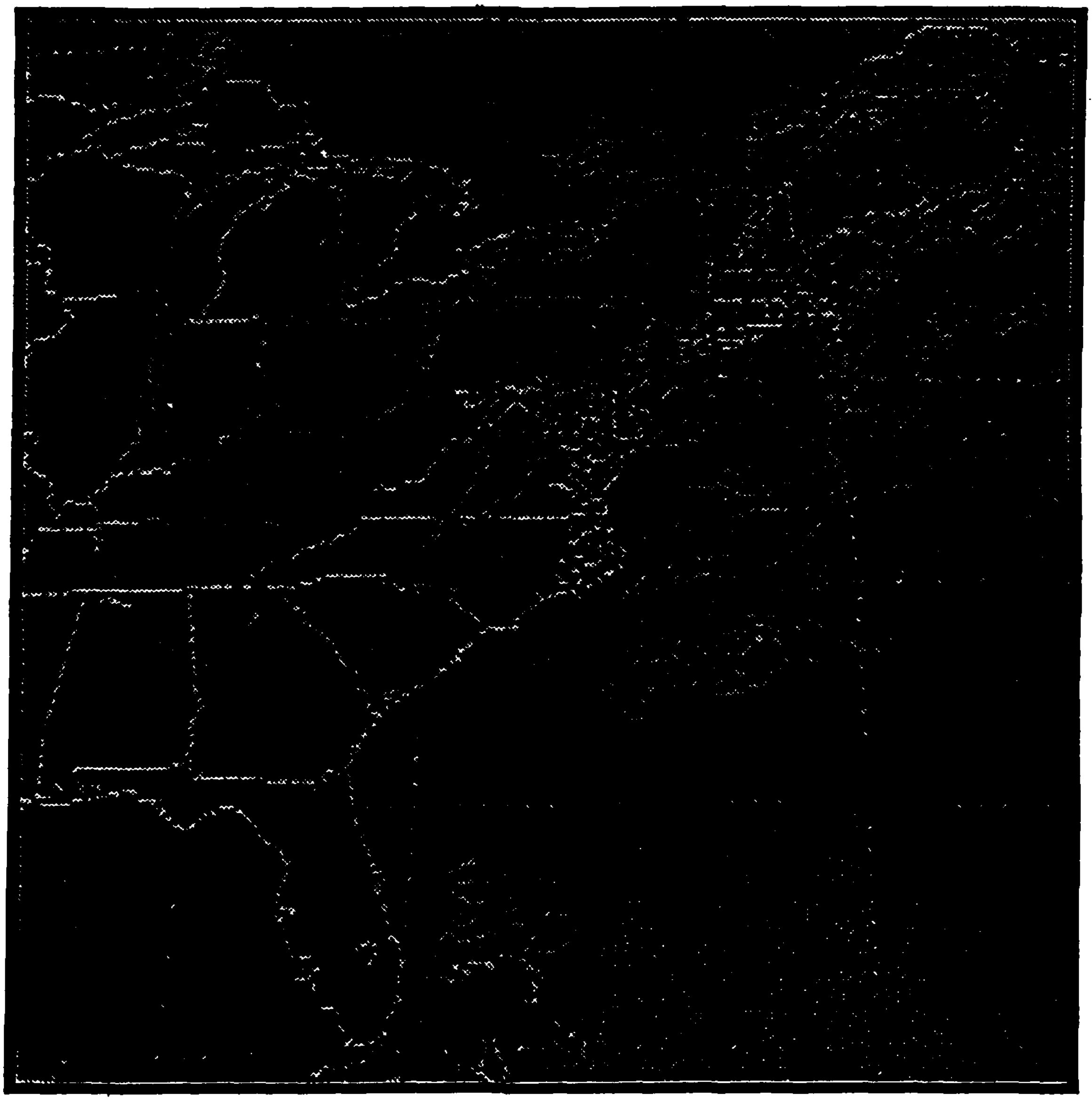

Figure 8 a. M_s **Enhanced satellite image for 0001 UTC, 11 November 1987.**

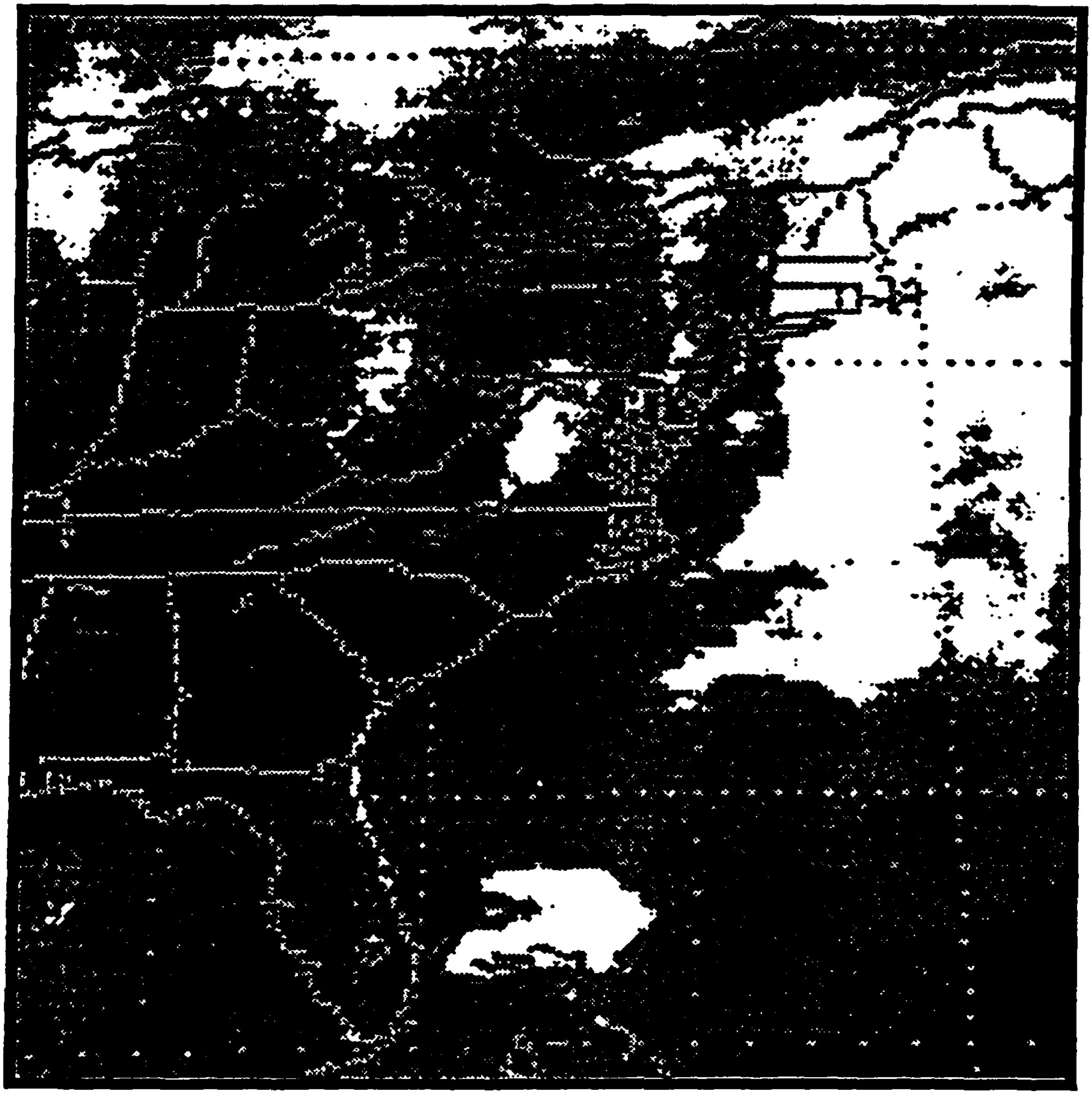

Figure 8 b. Satellite image enhanced for water vapor analysis for 0001 UTC, 11 November 1987. Dark (light) regions denote dry (moist) regions.

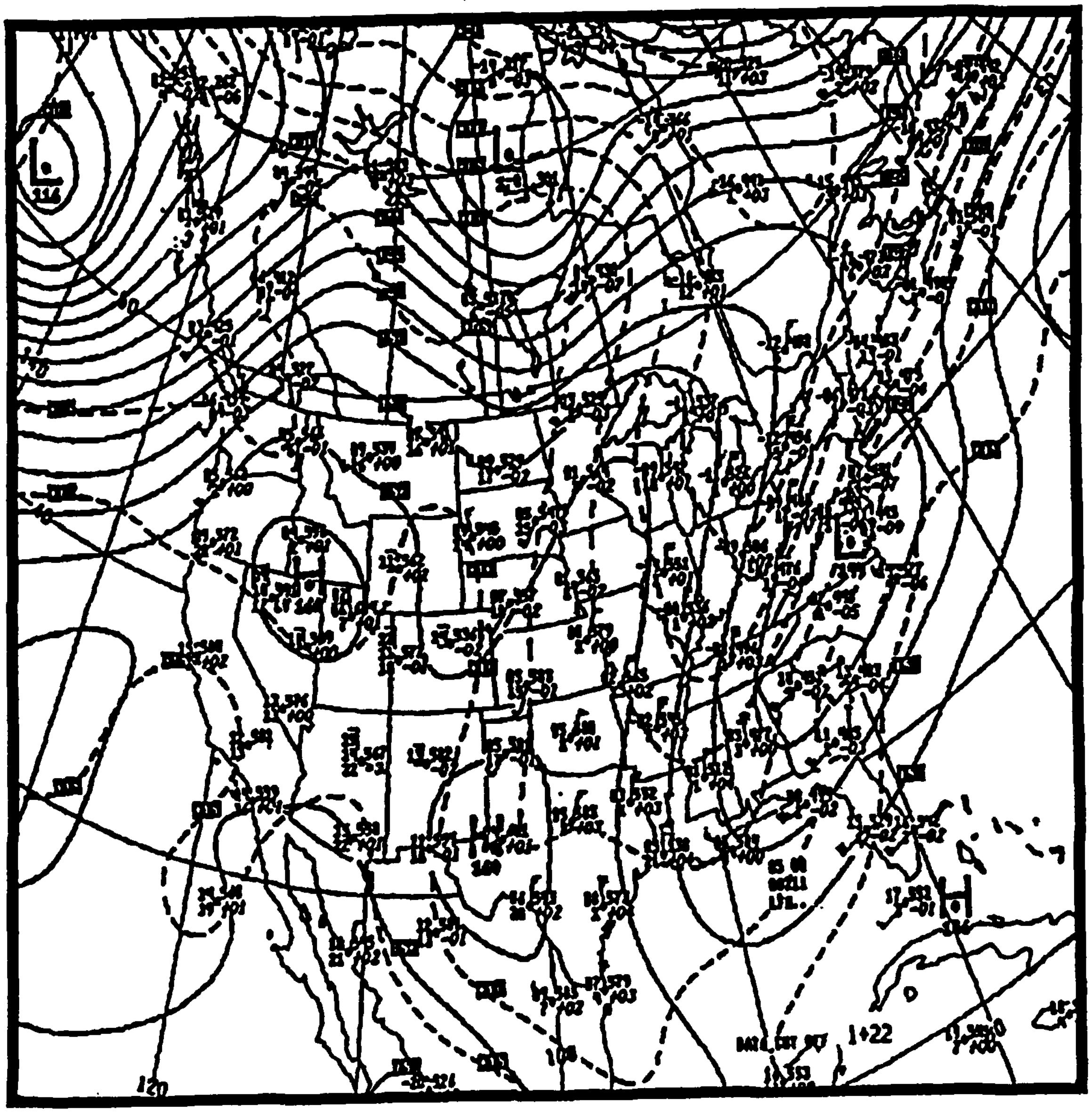

Figure 9. NMC 850 mb analysis for 0000 UTC, 11 November 1987.

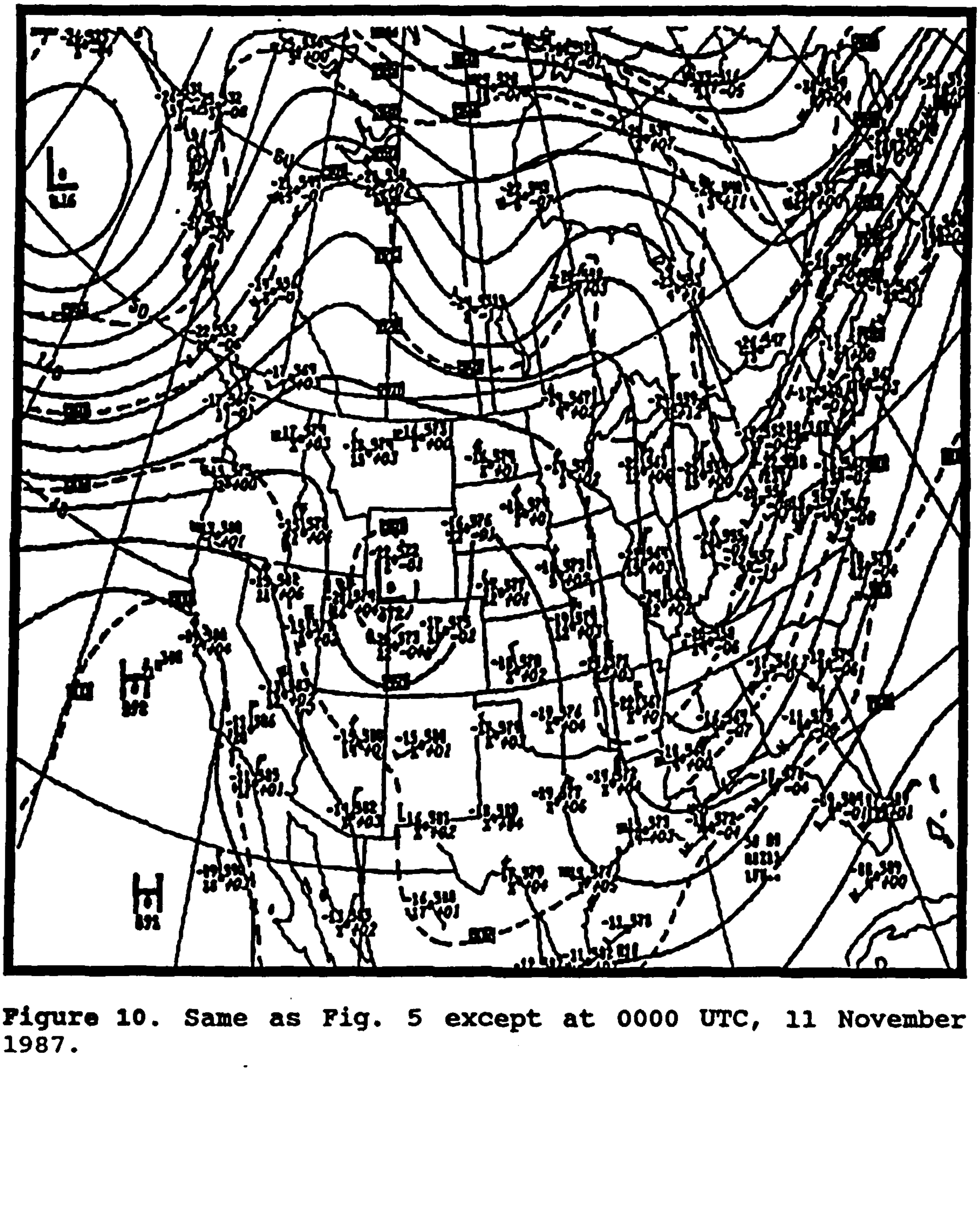

Figure 10. Same as Fig. 5 except at 0000 UTC, 11 November 1987.

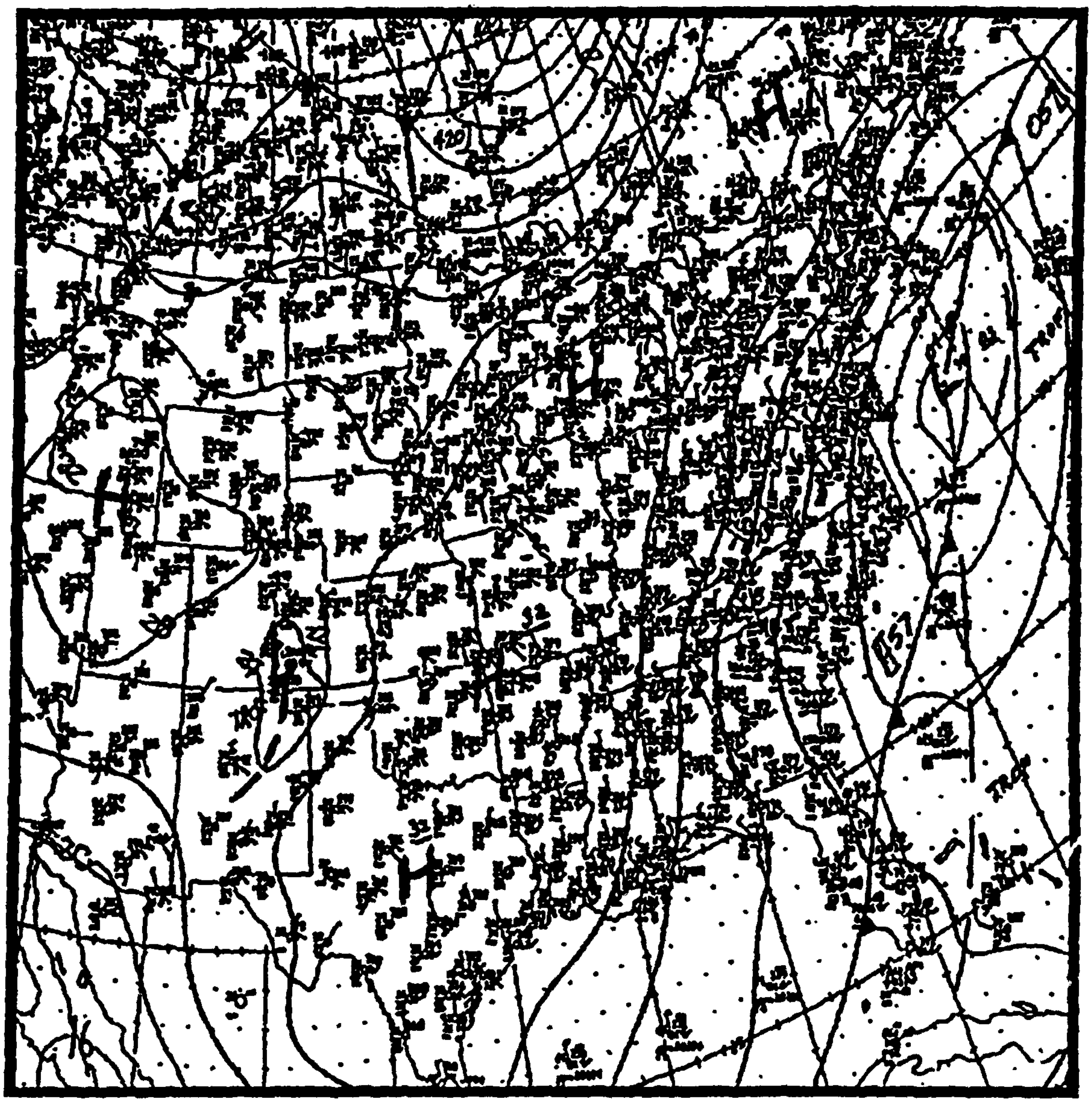

Figure 11. Same as Fig. 1 except at 1200 UTC, 11 November 1987.

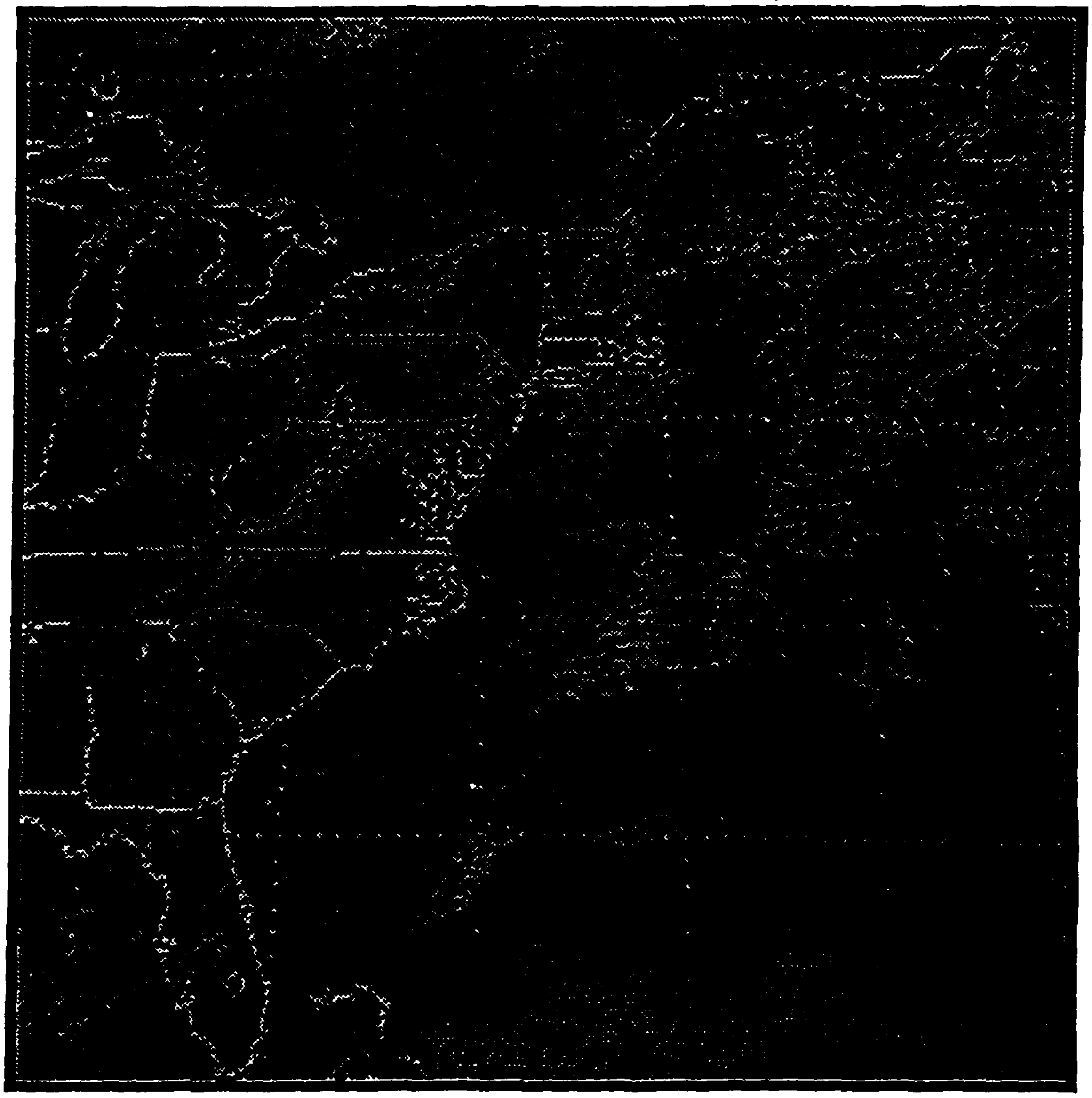

Figure 12. Same as Fig. 8a except at 1200 UTC, 11 November 1987.

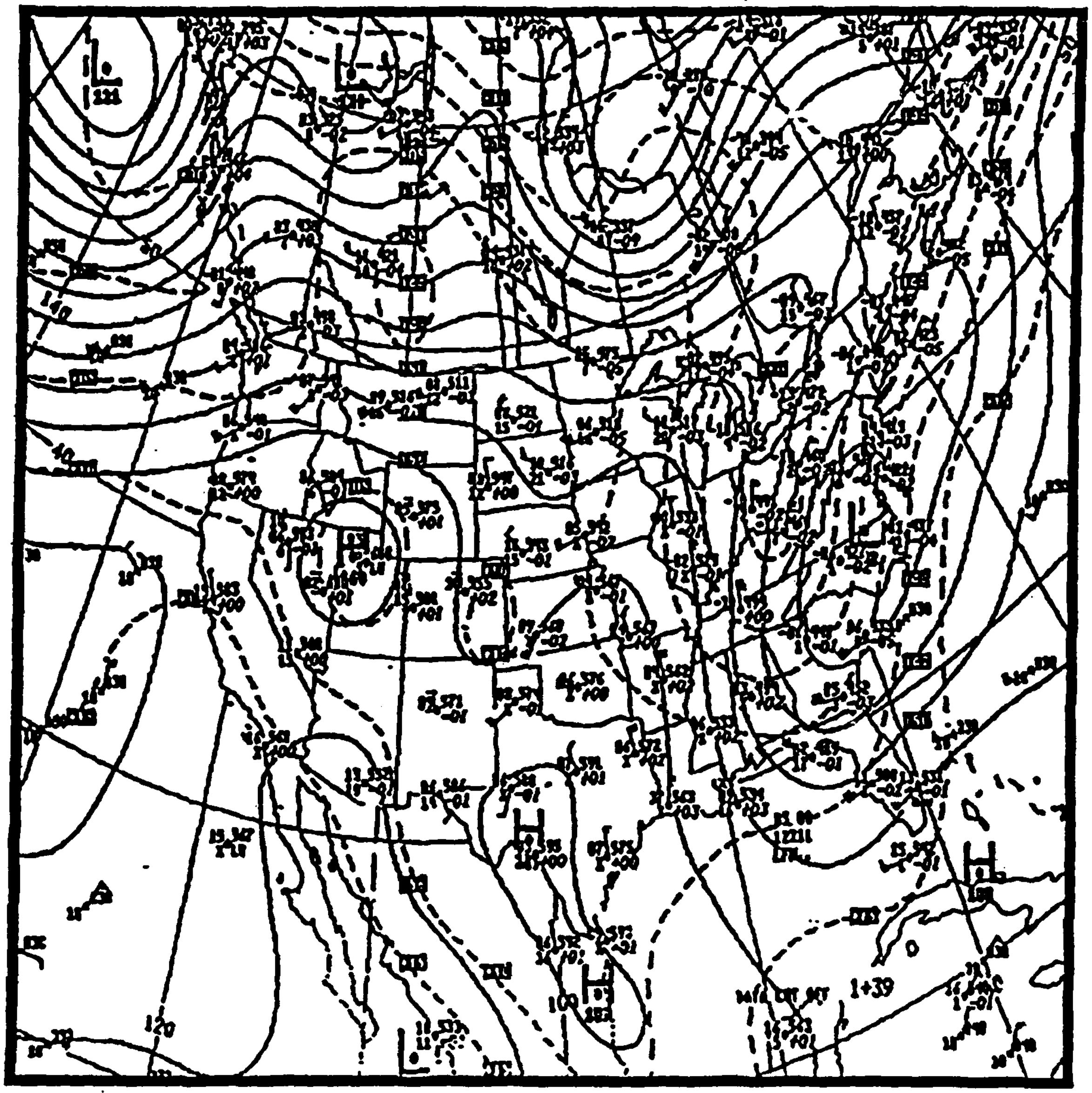

Figure 13. Same as Fig. 9 except at 1200 UTC, 11 November 1987.

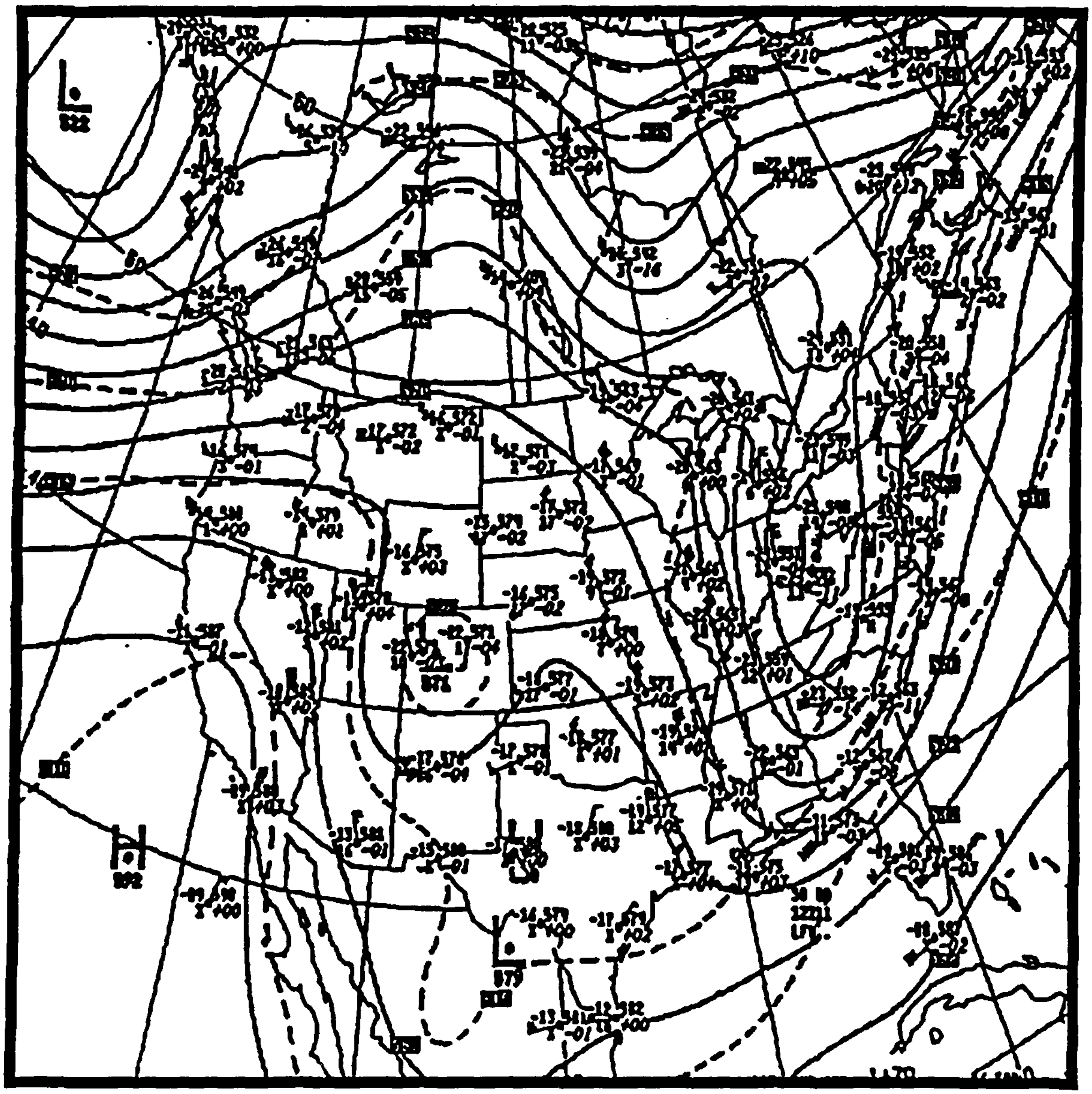

Figure 14. Same as Fig. 5 except at 1200 UTC, 11 November 1987.

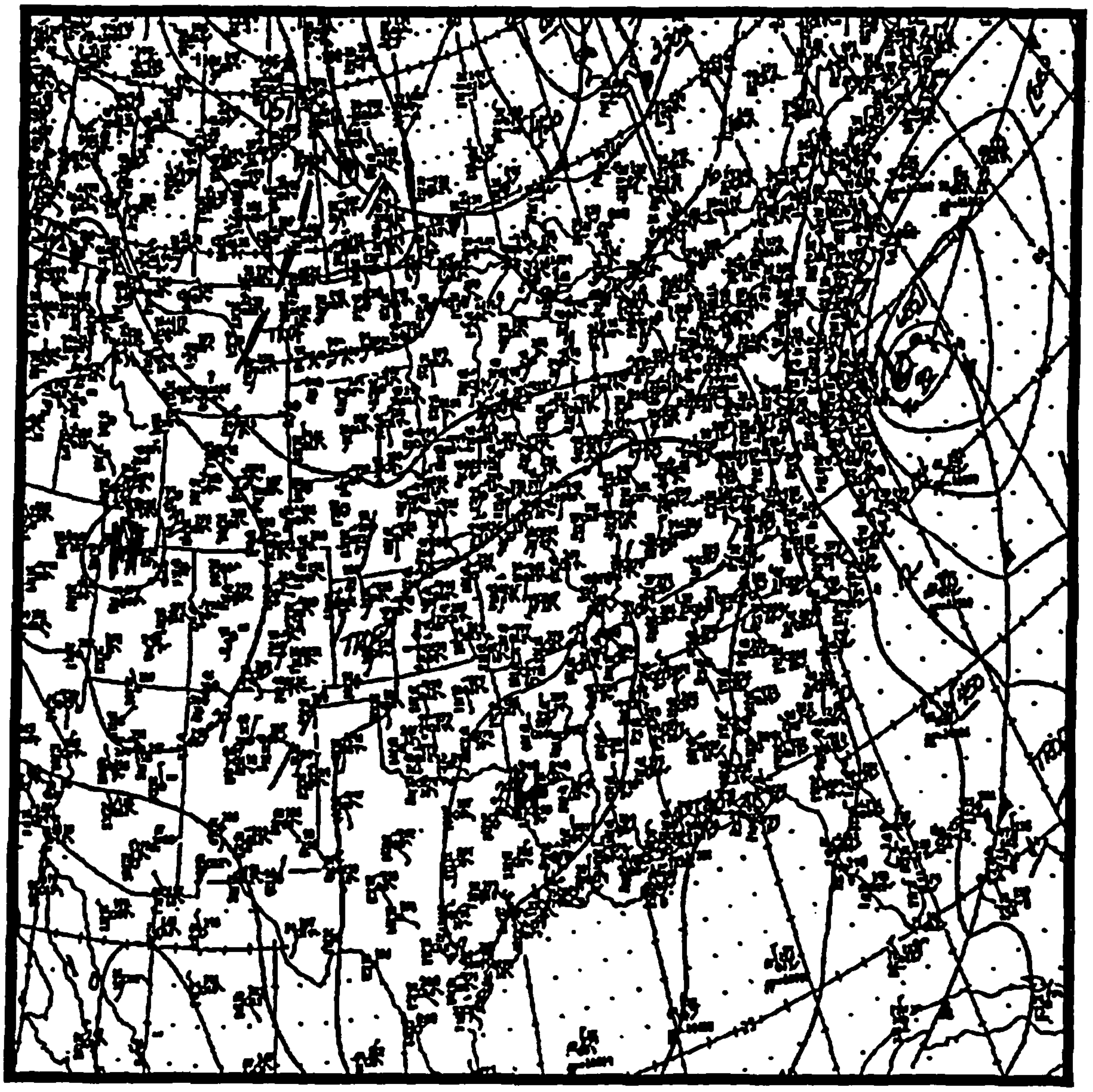

Figure 15. Same as Fig. 1 except at 0000 UTC, 12 November 1987.

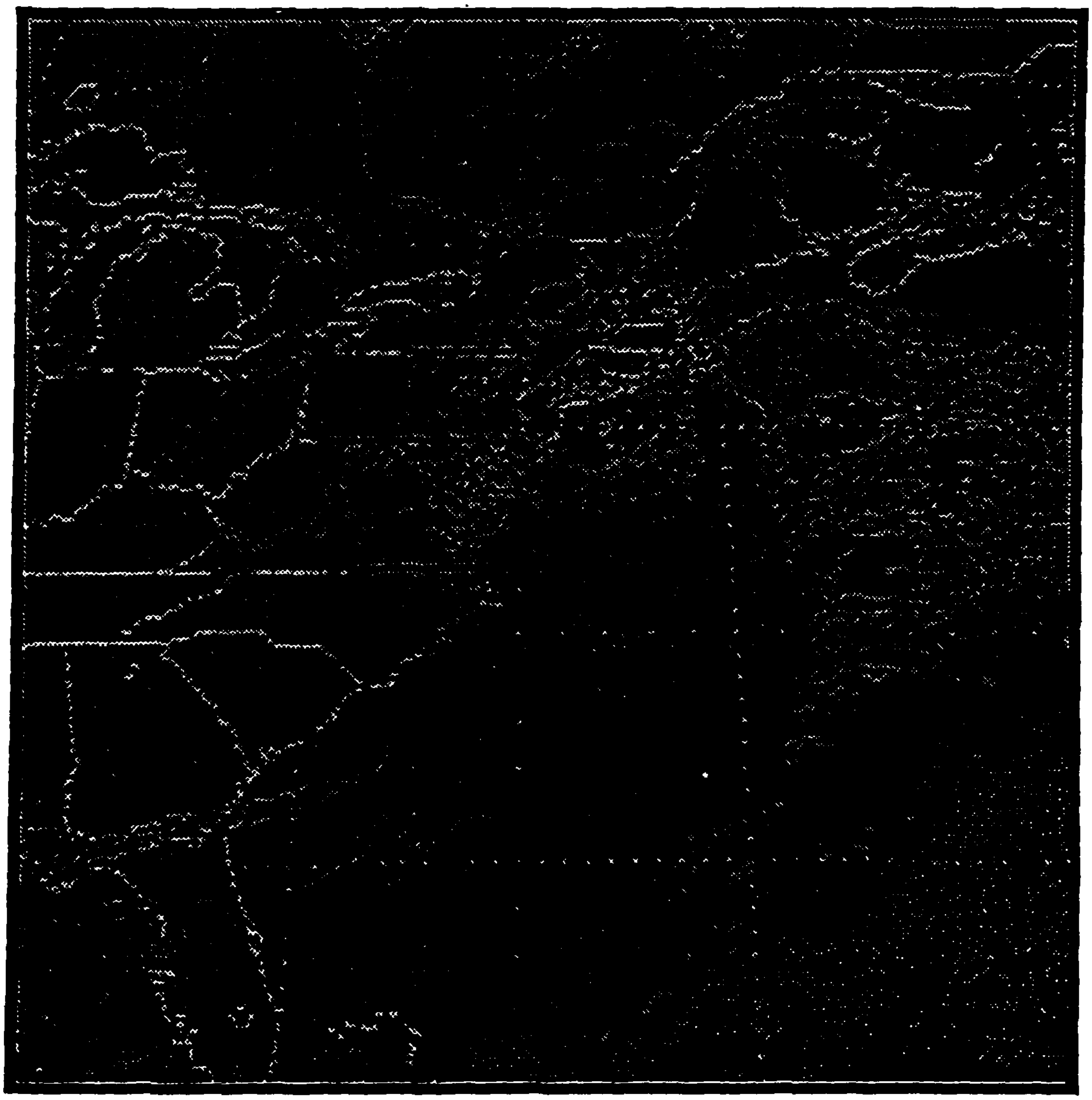

Figure 16. Same as Fig. 8a except at 0001 UTC, 12 November 1987.

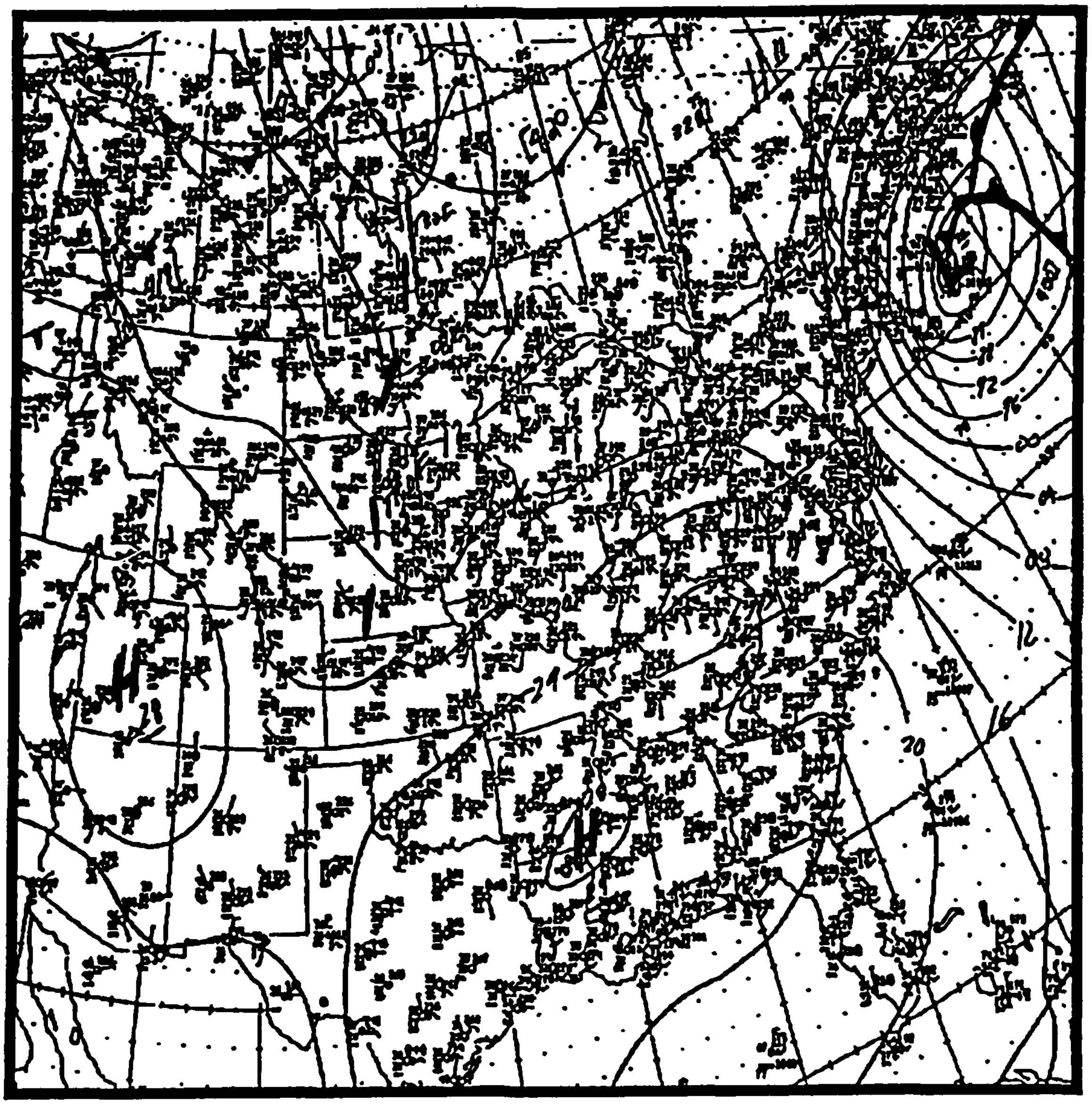

Figure 17. Same as Fig. 1 except at 1200 UTC, 12 November 1987.

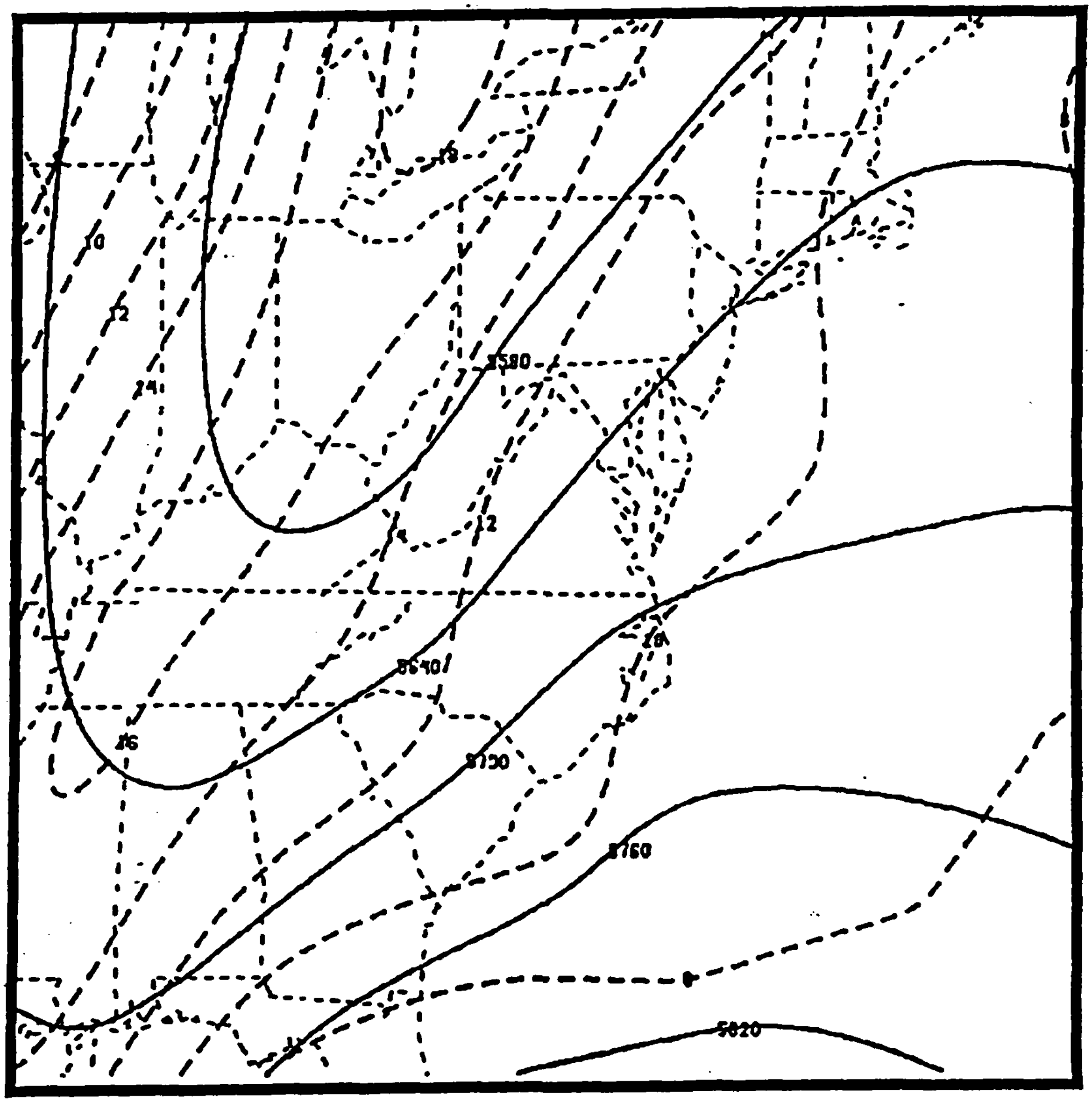

Figure 18. 500 mb height (solid lines) and absolute vorticity (dashed lines in units of $10^{-5}s^{-1}$).

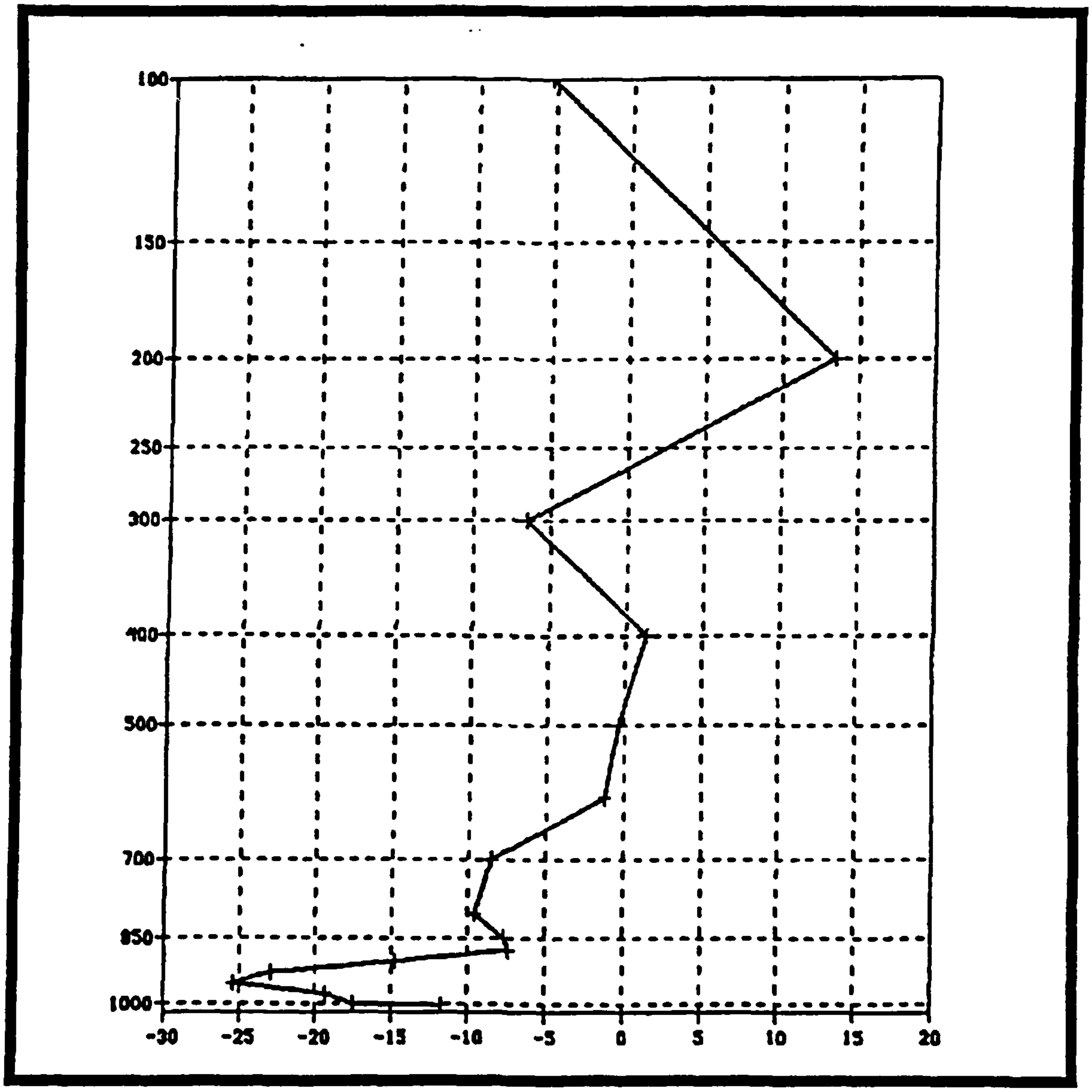

Figure 19. Vertical profile of horizontal divergence (in units of $10^{-5}s^{-1}$) measured at Cape Hatteras, N.C. (HAT) for 0000 UTC, 11 November 1987. Positive (negative) values indicate divergence (convergence).

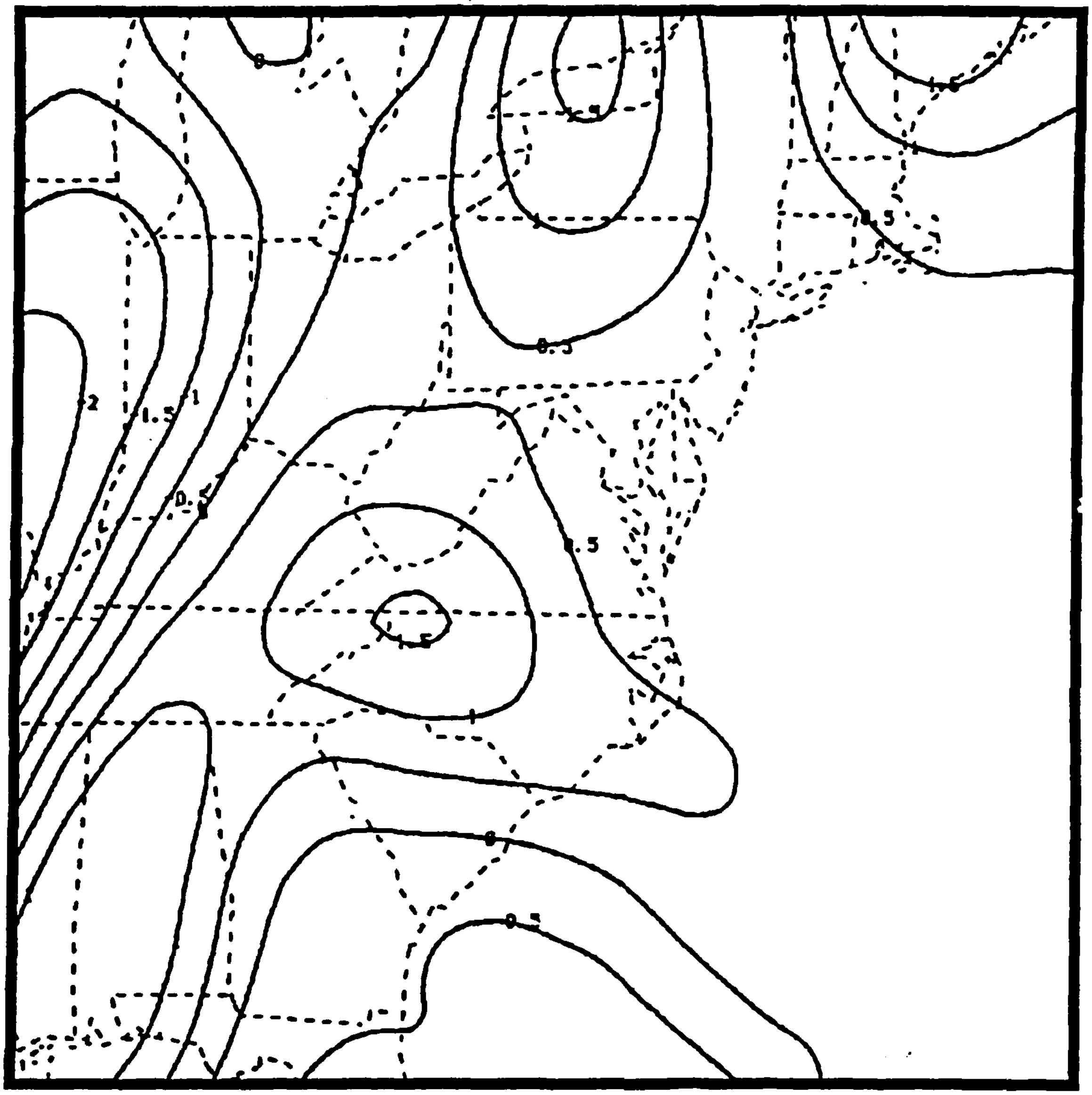

Figure 20. Horizontal advection of absolute vorticity (in units of $10^{-9}s^{-2}$) at 0000 UTC, 11 November 1987.

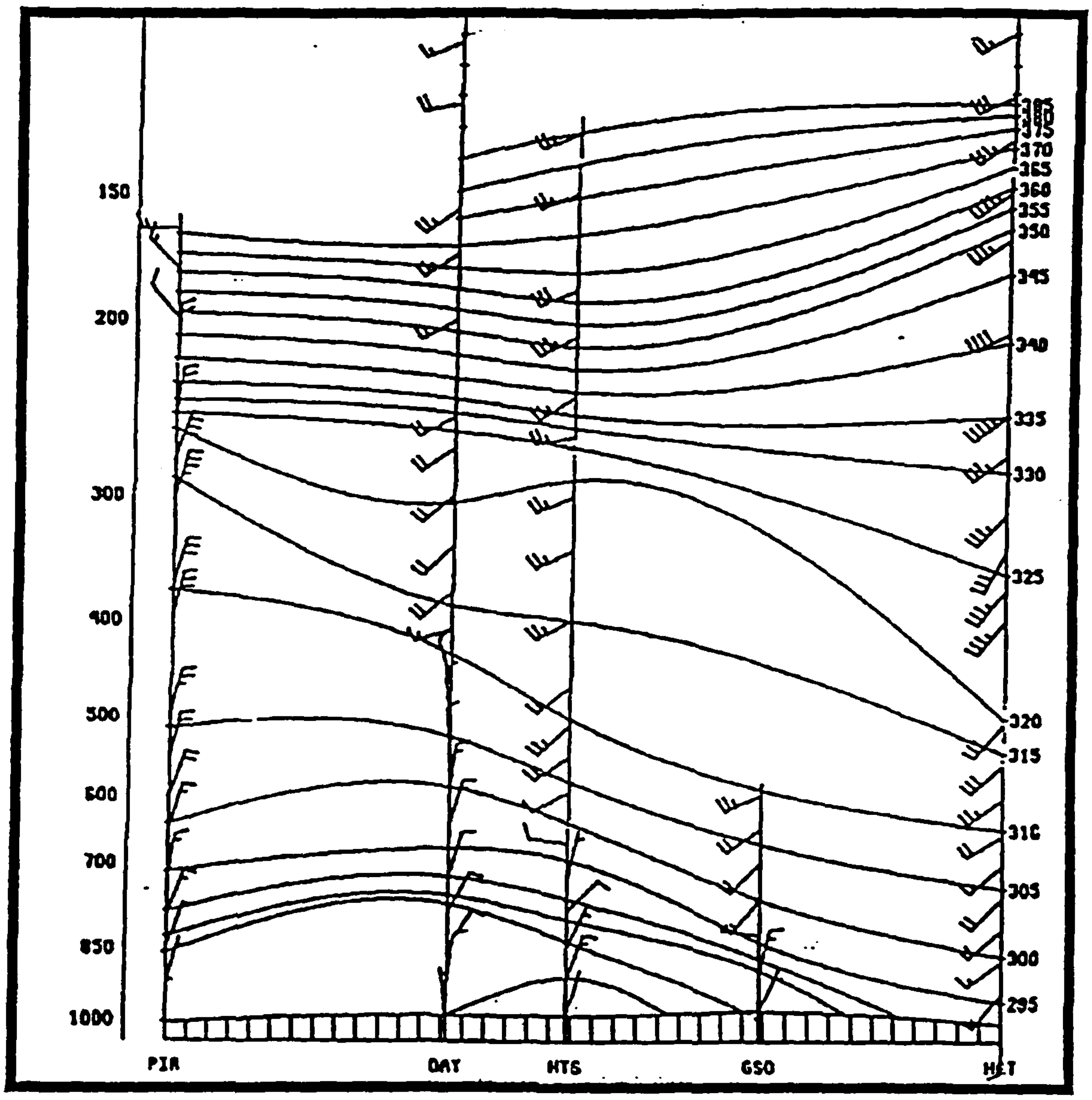

Figure 21. Vertical cross section from Peoria, IL. (PIA) eastward to Cape Hatteras, N.C. (HAT). Isolines indicate constant equivalent potential temperature surfaces. (temperature is in K)

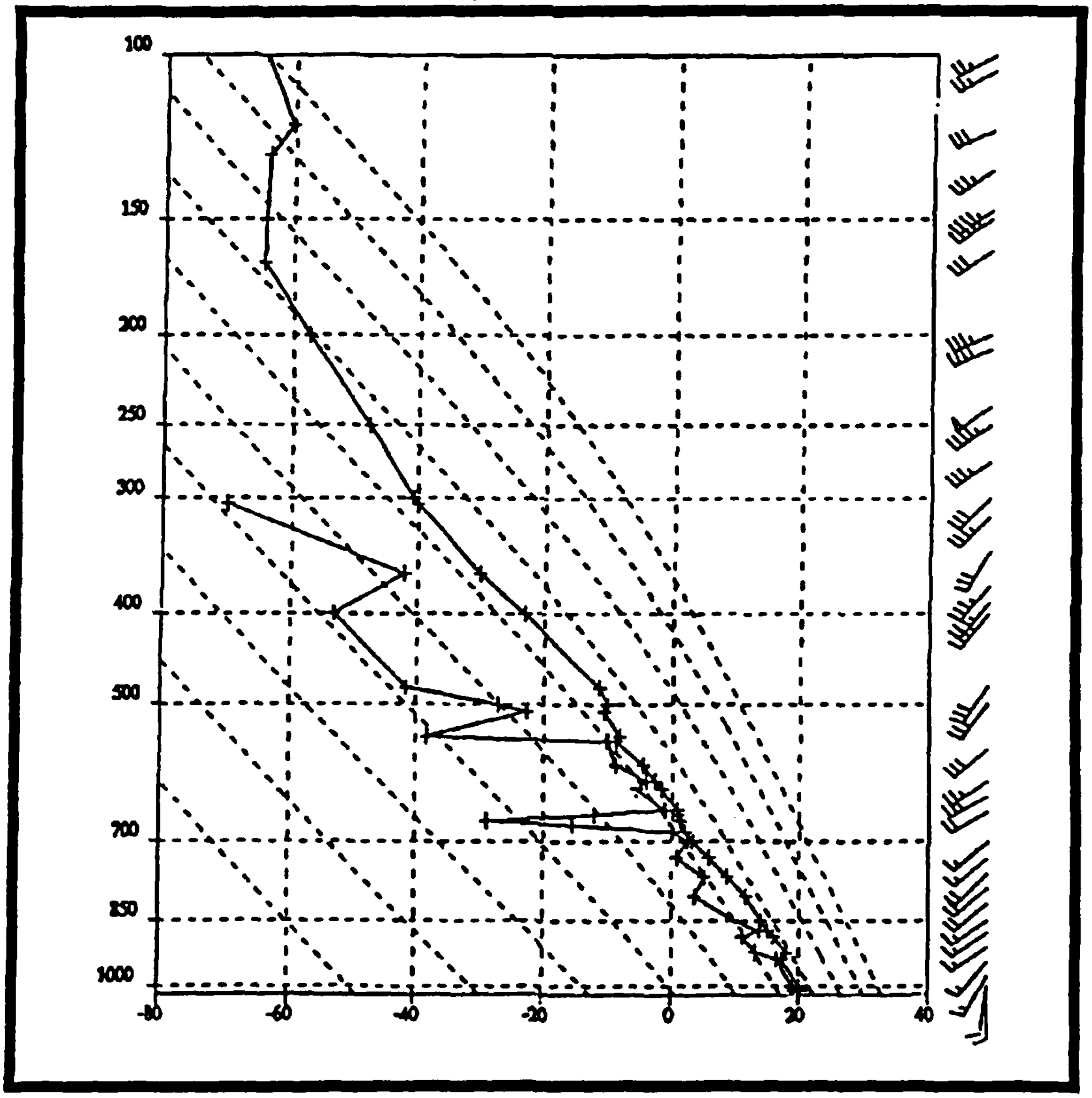

Figure 22. Vertical profile of temperature and dewpoint over (HAT) at 0000 UTC, 11 November 1987. Wind velocity is in m/s.

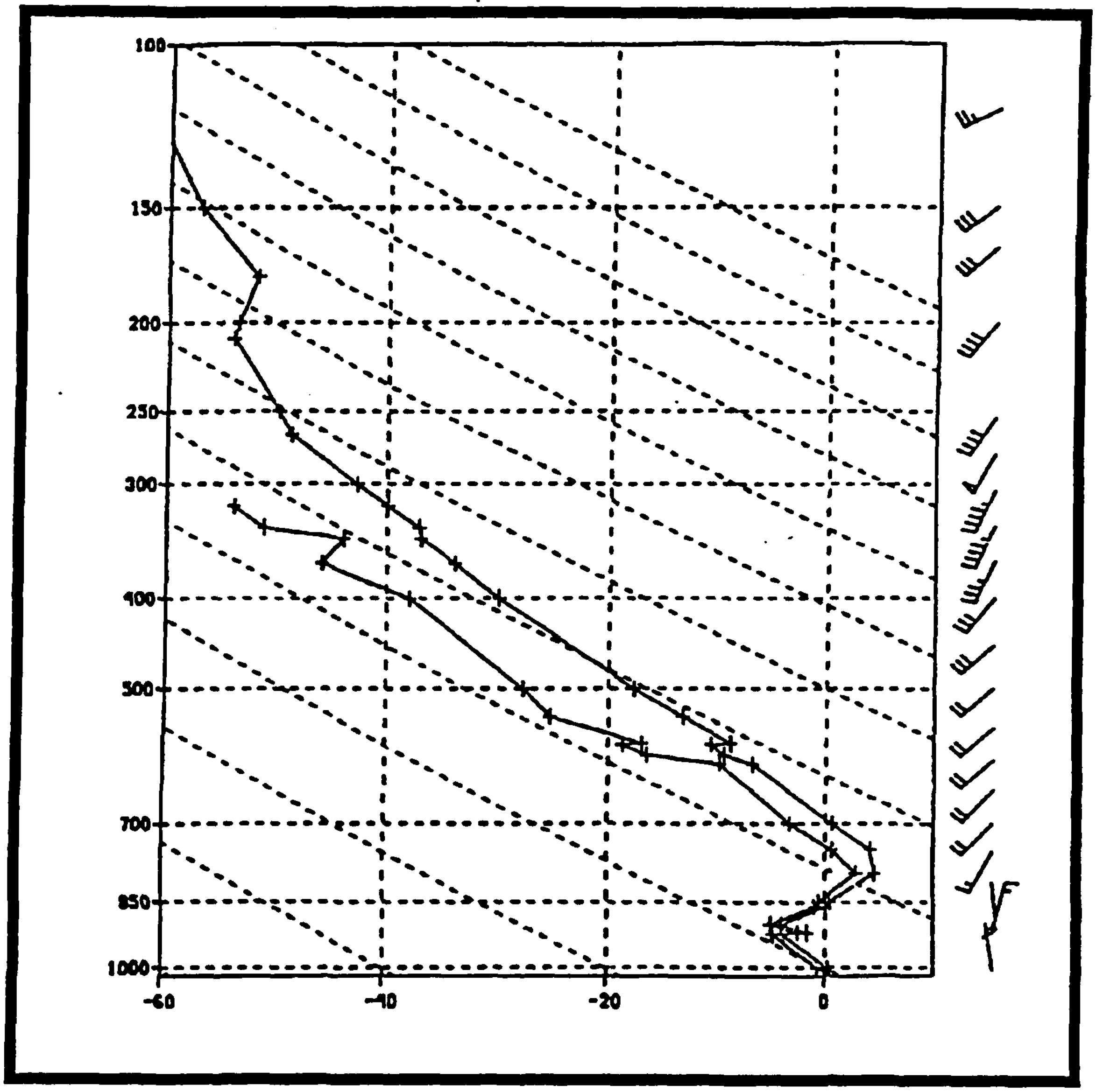

Figure 23. Same as Fig. 22 except at Dulles International Airport (IAD).

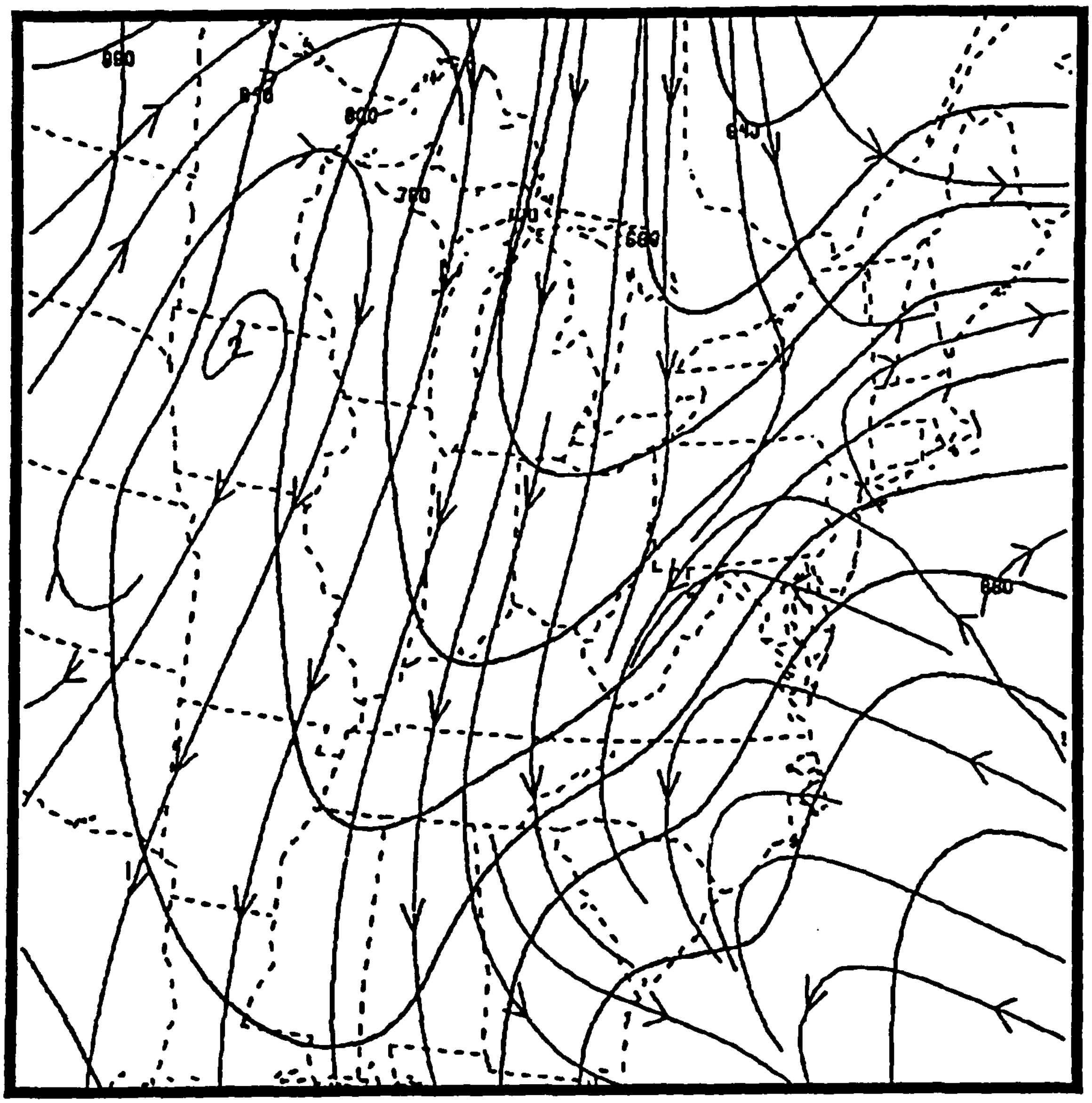

Figure 24. Streamlines (with arrows) and isobaric (heavy solid lines) analysis on the 290 K isentropic surface for 0000 UTC, 11 November 1987. Isobars at 40 mb increments.

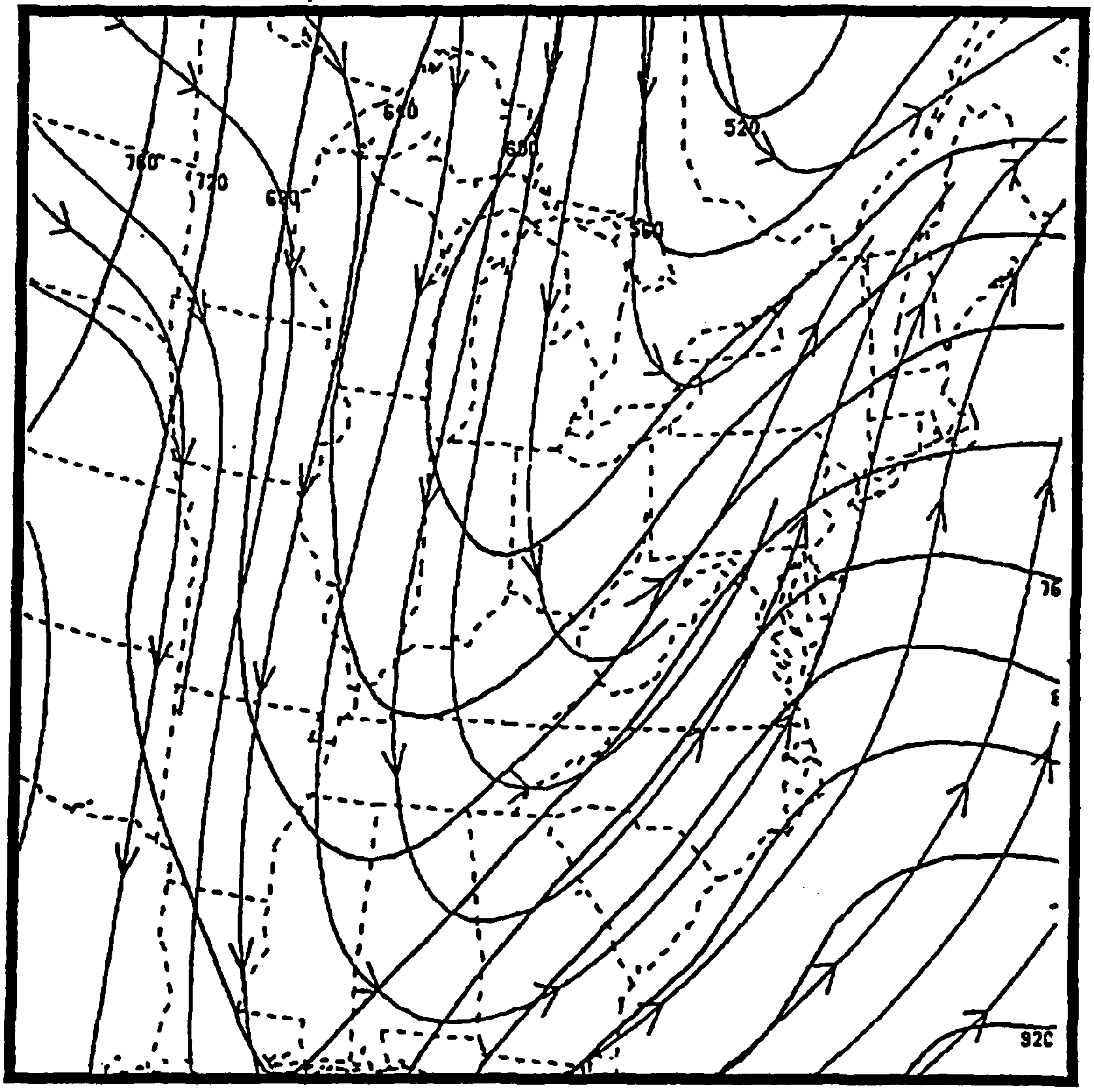

Figure 25. Same as Fig. 24 except at 300 K.

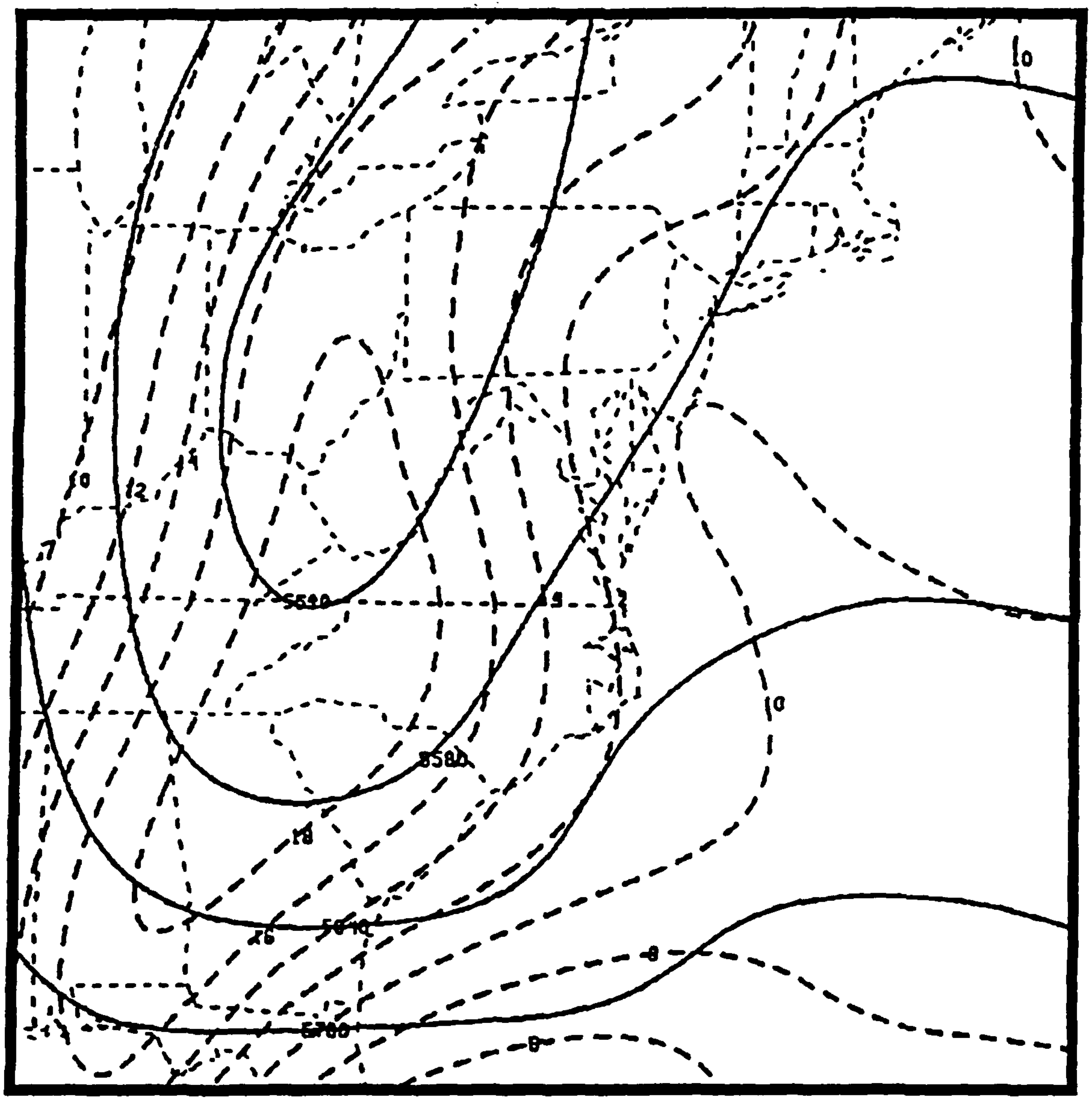

Figure 26. Same as Fig. 18 except at 1200 UTC, 11 November 1987.

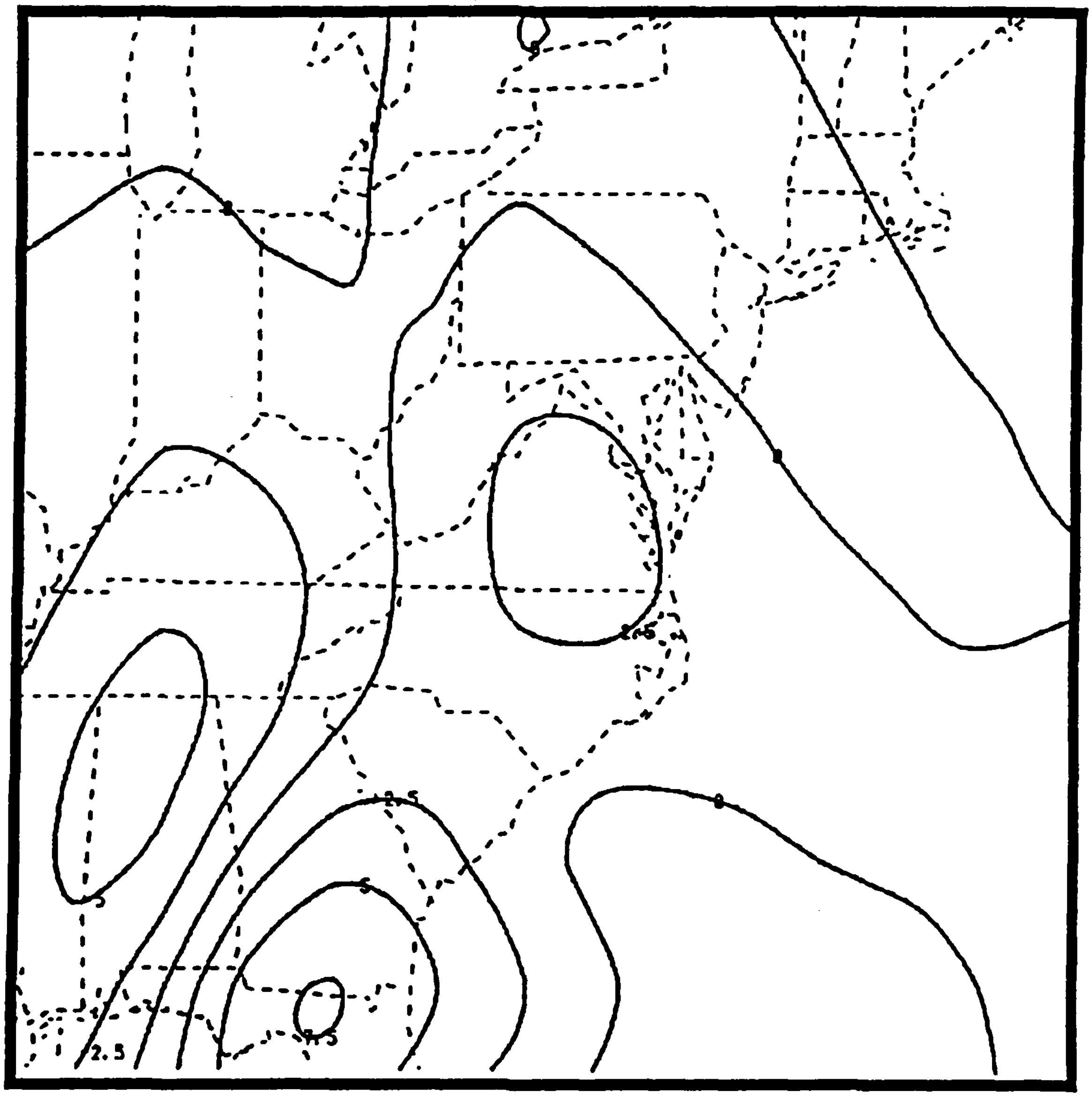

Figure 27. Same as Fig. 20 except at 1200 UTC 11 November 1987.

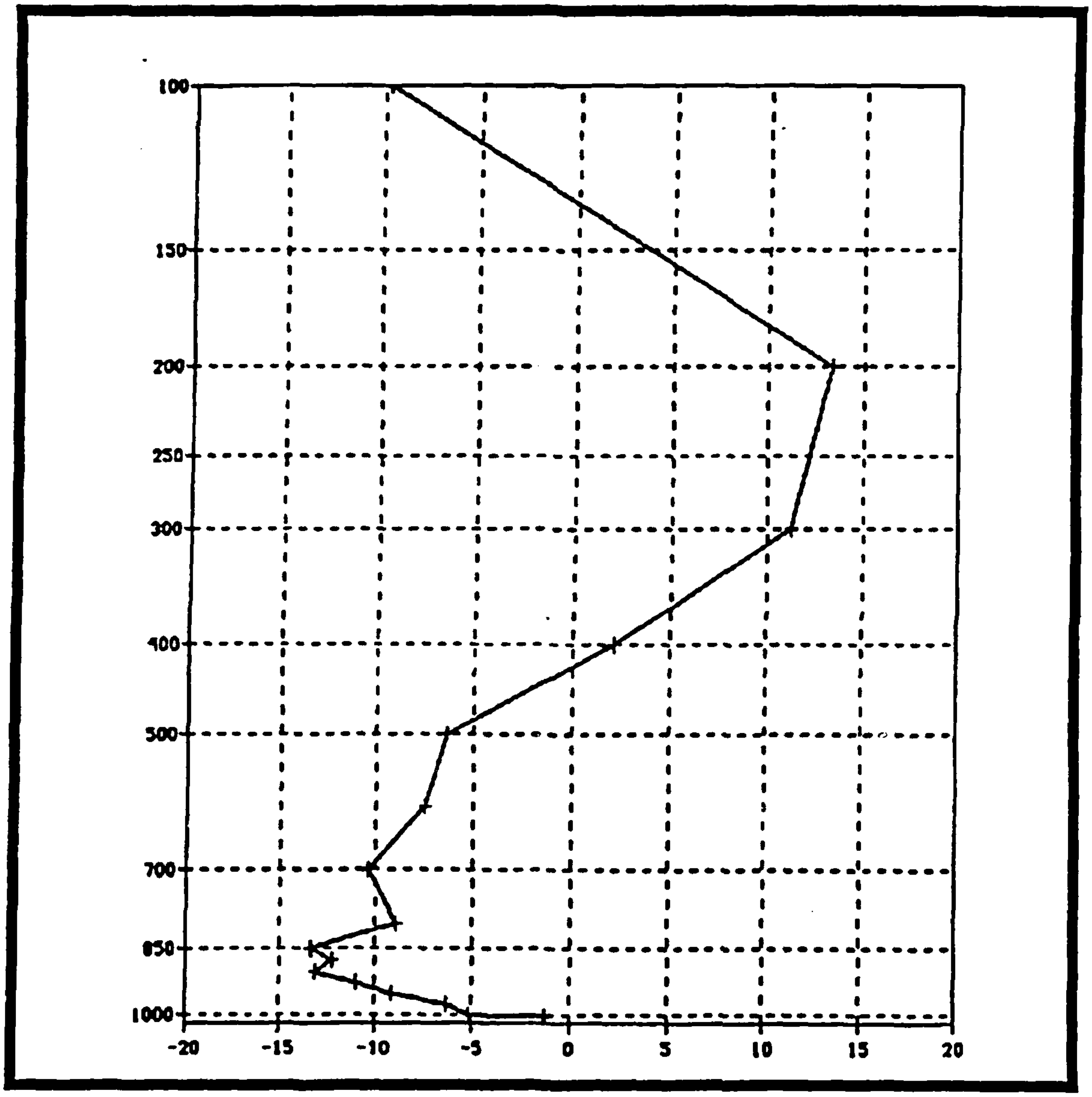

Figure 28. Same as Fig. 19 except at 1200 UTC, 11 November 1987.

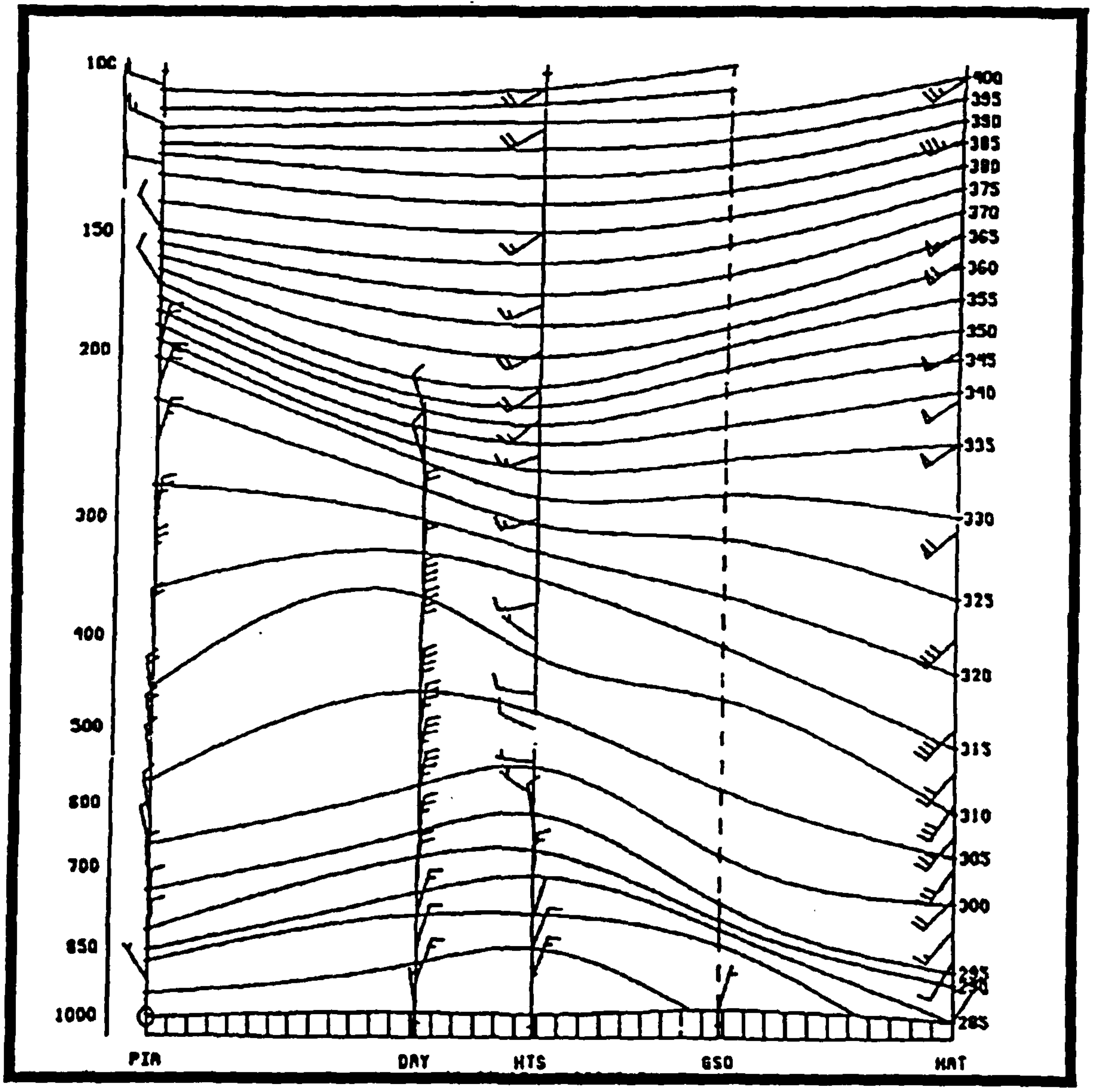

Figure 29. Same as Fig. 21 except at 1200 UTC, 11 November 1987.

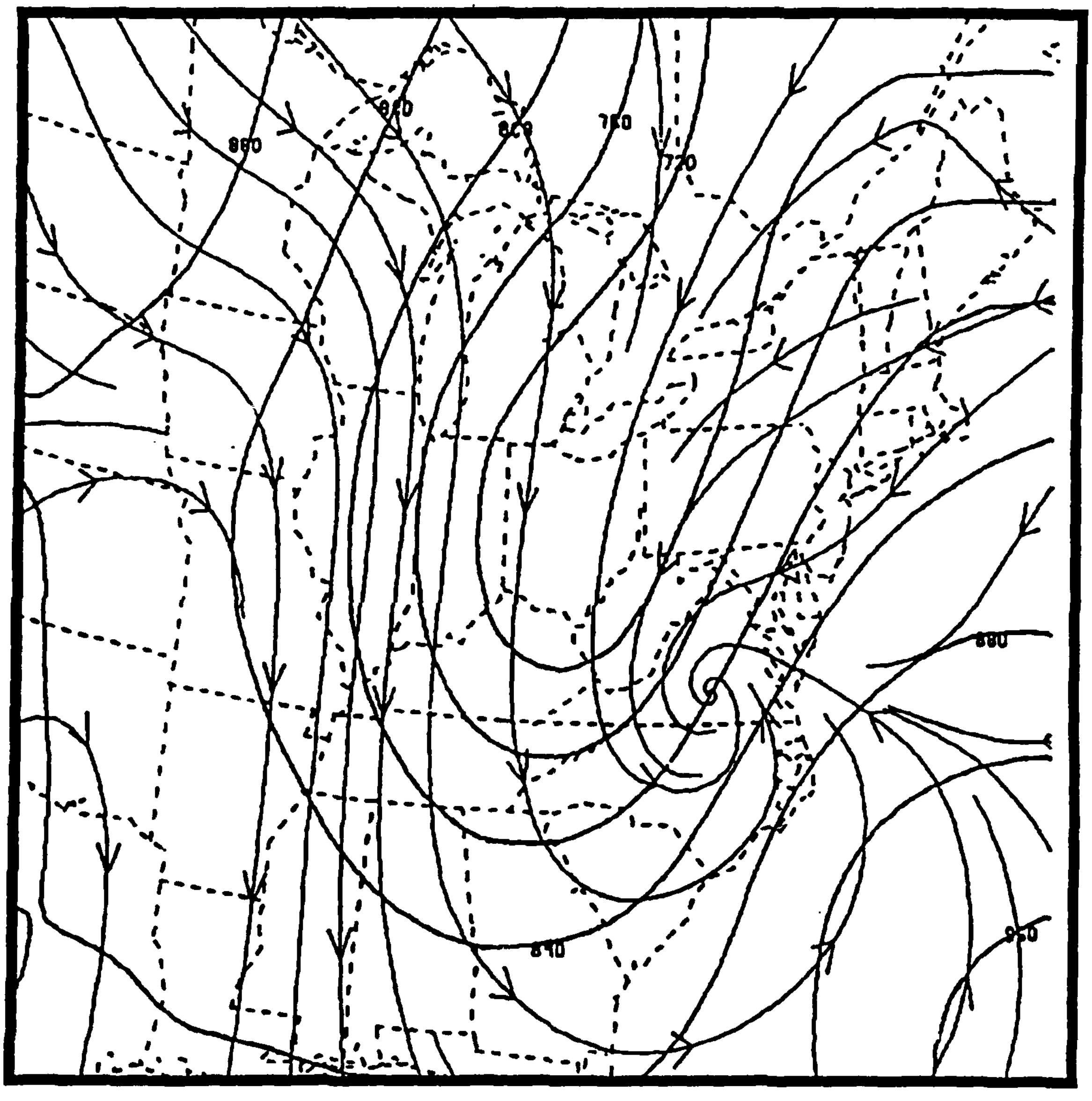

Figure 30. Same as Fig. 24 except at 1200 UTC, 11 November 1987.

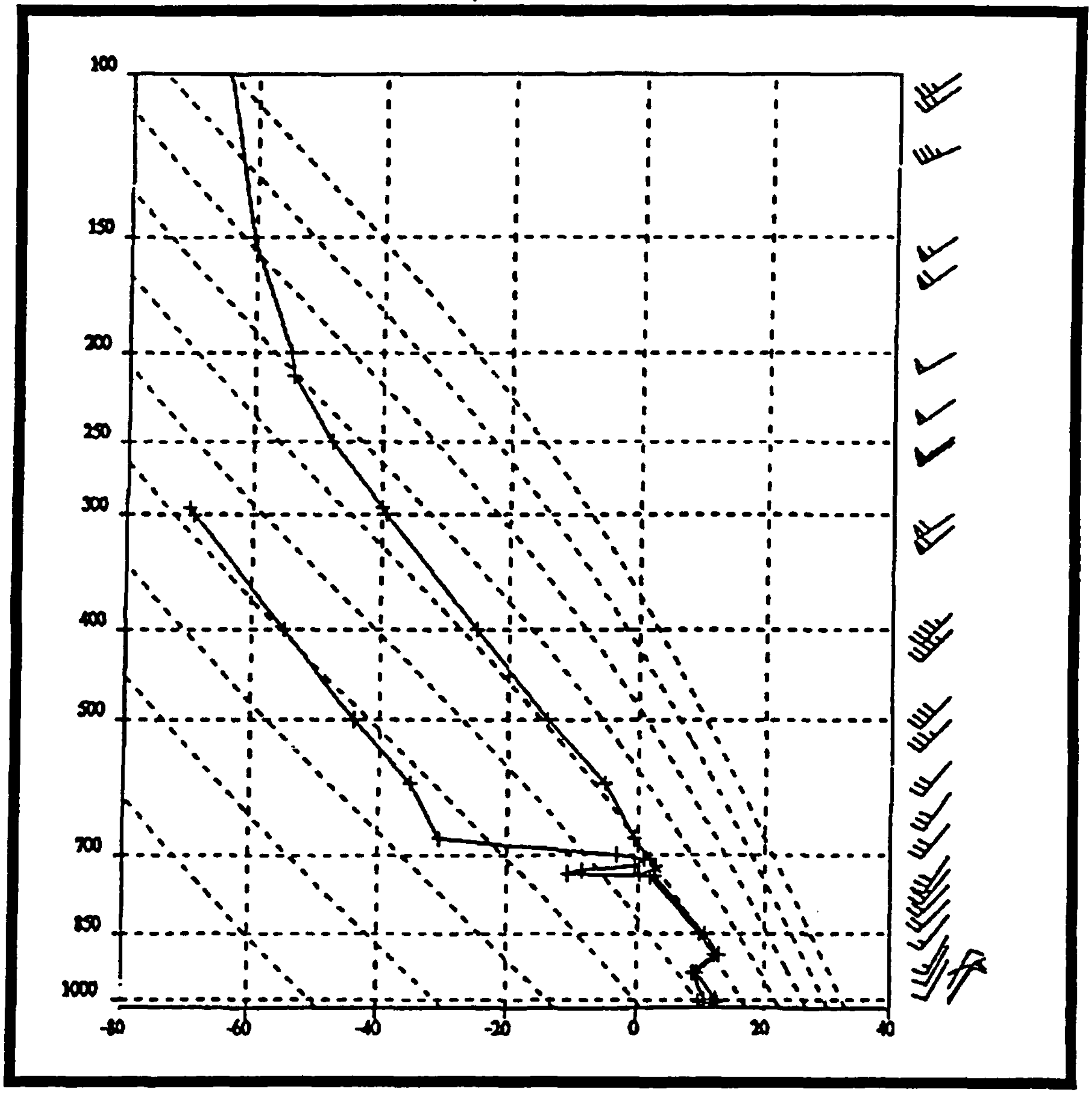

Figure 31. Same as Fig. 22 except at 1200 UTC, 11 November 1987.

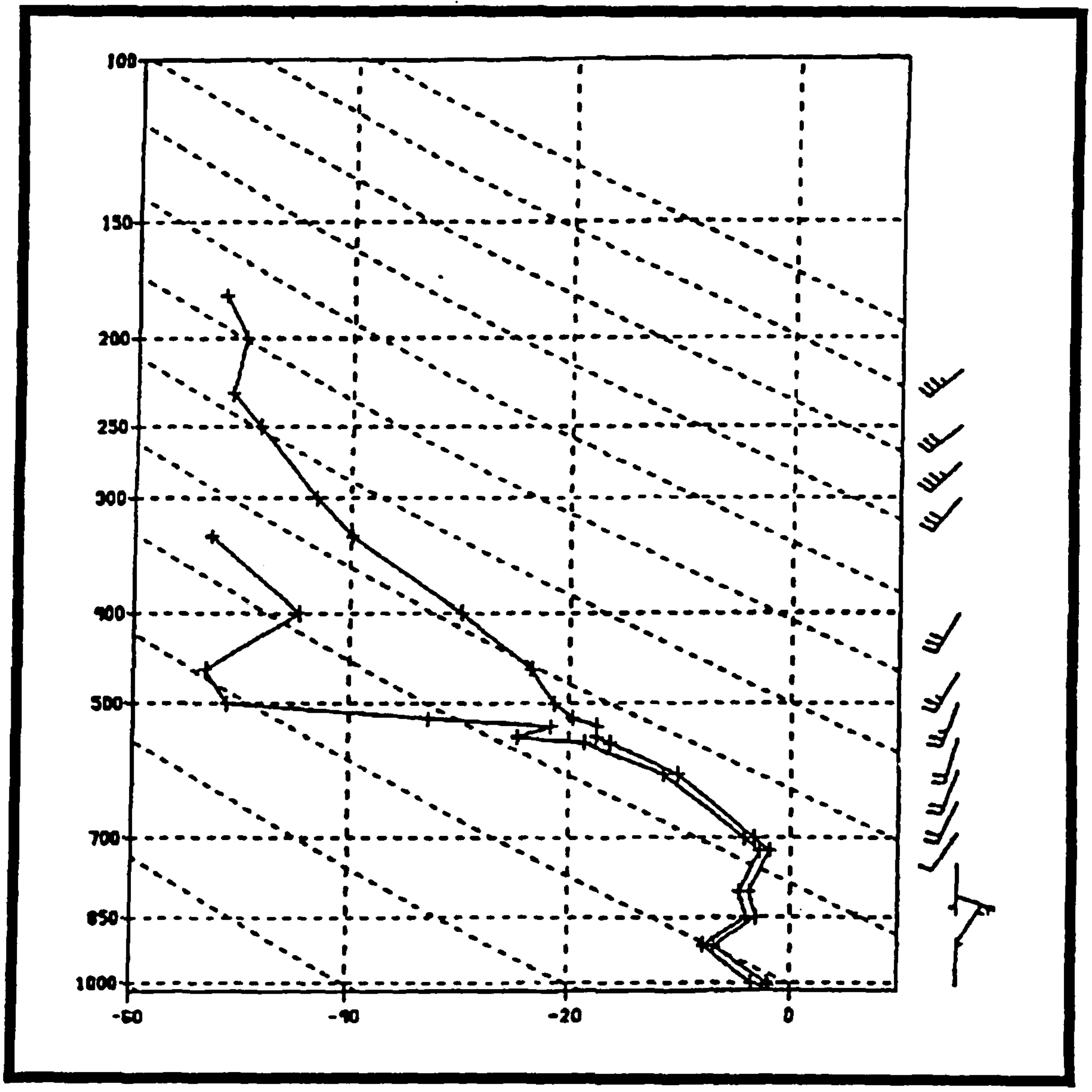

Figure 32. Same as Fig. 23 except at 1200 UTC, 11 November 1987.

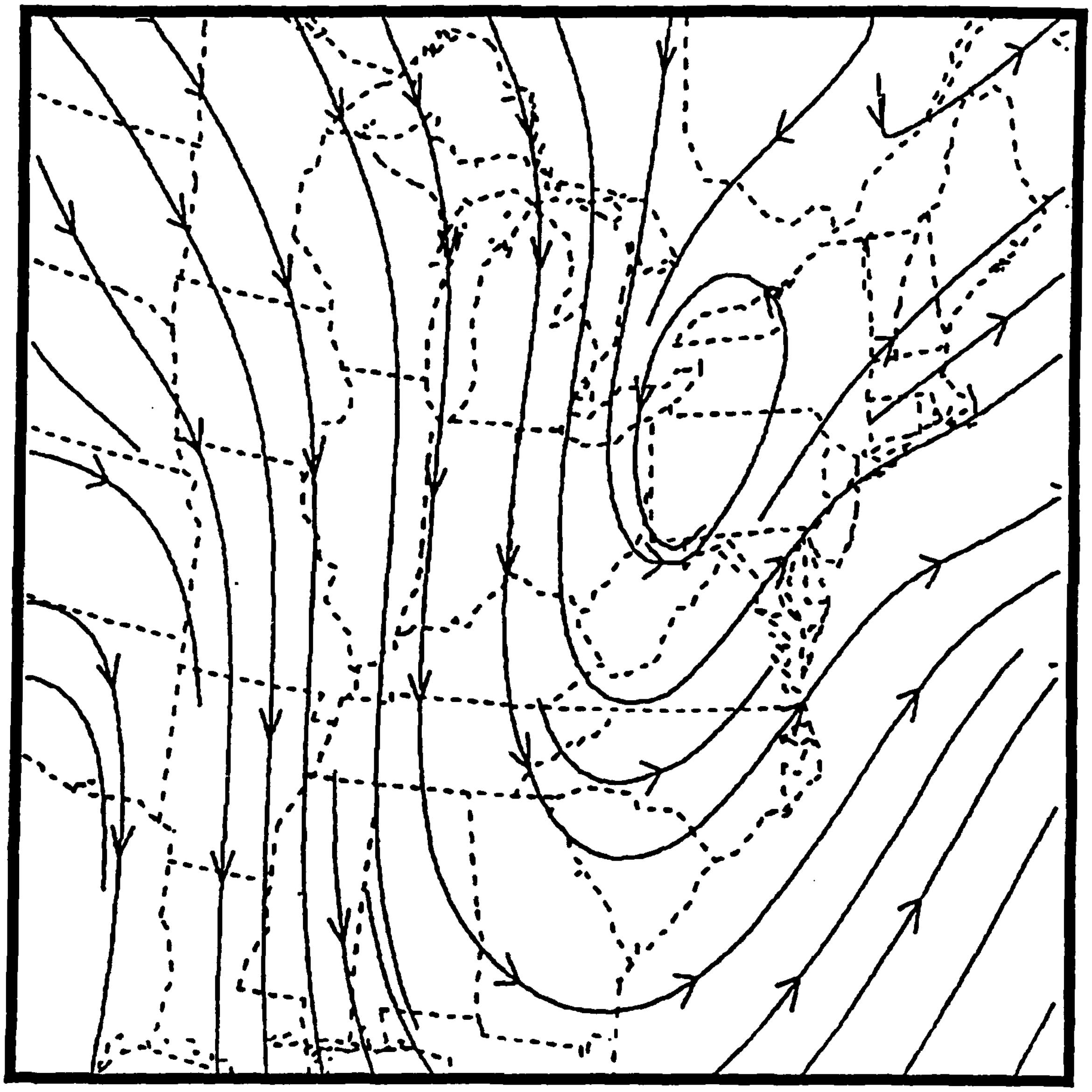

Figure 33. Same as Fig. 25 except at 1200 UTC, 11 November 1987.

Figure 34. Analysis of sea surface temperature gradients over the Gulf Stream. The North Wall is defined by the sharp temperature contrast (black to white) acoss the ocean front. Two cold eddies lie south of the North Wall and are marked for clarity.

Figure 35. Same as Fig. 34 except that storm development and track are denoted on the image. Storm developed over the strong SST gradient but then followed the 500 mb flow pattern after 0900 UTC, 12 November 1987.

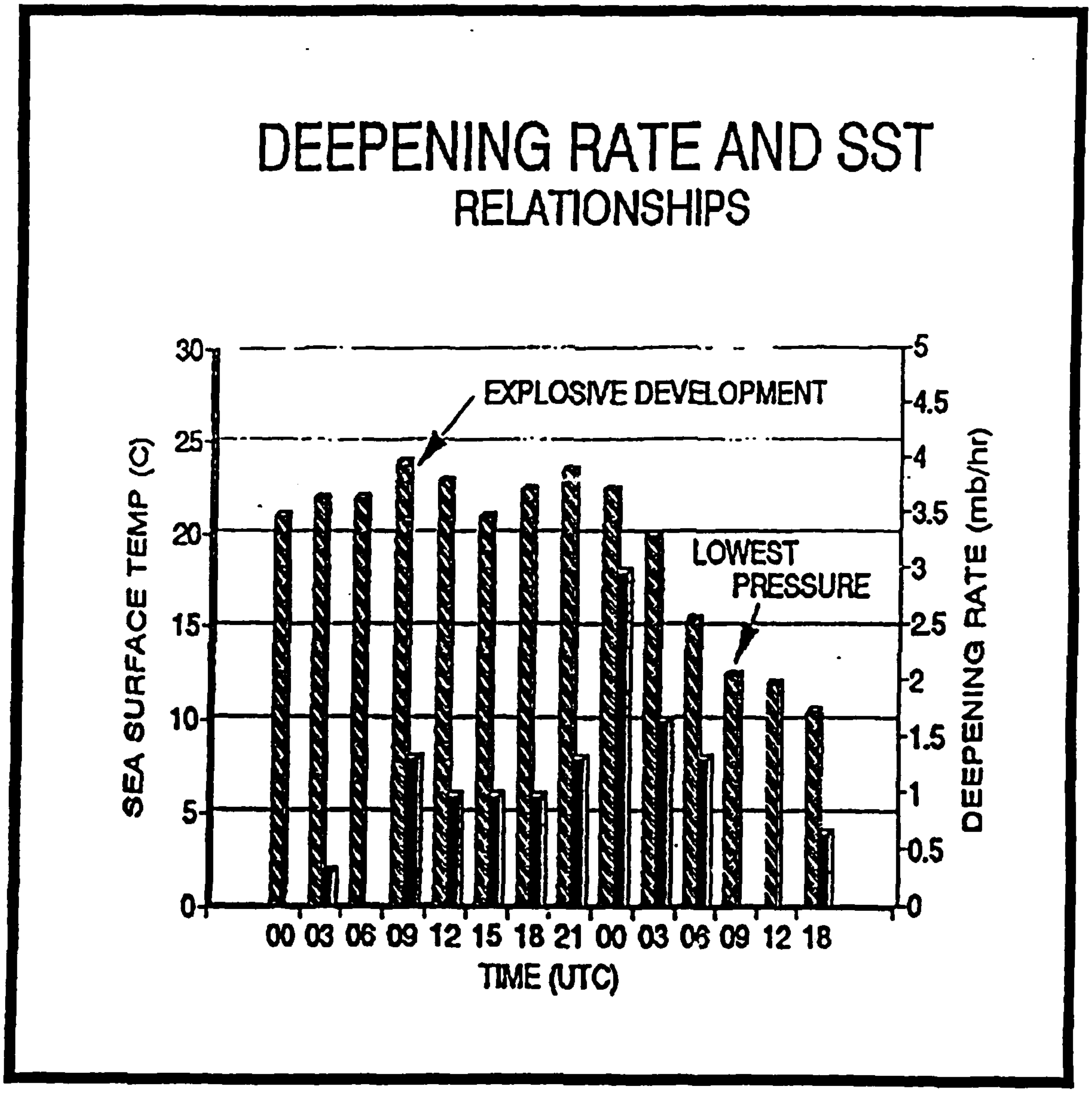

Figure 36. The diagram above suggests the relationship between sea surface temperature (hatched bars) and deepening rate (solid bars) from 0000 UTC on 11 November to 1800 UTC on 12 November.

Appendix 1: List of Symbols

f : Coriolis force (planetary vorticity).

$\frac{\partial}{\partial p}$: Change with respect to pressure.

V_g : Geostrophic wind velocity.

V_H : Horizontal wind velocity.

$-\frac{\partial \Phi}{\partial p}$: Change in geopotential height.

ζ : Relative vorticity.

$(\zeta + f)$: Absolute vorticity (sum of relative and planetary).

σ : Static stability parameter.

$\nabla \cdot V_H$: Horizontal divergence.

w : Vertical velocity in pressure coordinates.

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